Study on Mechanical Properties and Crack Propagation of Raw Coal with Different Bedding Angles based on CT Scanning

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ABSTRACT: The deformation and damage characteristics of coal are the important foundation that affects the fracturing potential of coal reservoirs and the development plan of coalbed methane (CBM). To reveal the influence regulation of primary fractures and the bedding angle of coal on its failure and provide theoretical basis for CBM development, raw coal samples of no 16 coal seam in Wenjiaba Coal Mine, Zhijin County, Bijie City with different bedding angles were selected as the research object, and uniaxial compression tests were carried out on them, and CT scanning and crack reconstruction before and after sample failure were carried out. The results show that (1) the compressive strength, elastic modulus, and Poisson’s ratio of coal show a strong bedding angle effect, and the changing trend of each index is basically the same. The coal samples with bedding angles of 0 and 90° are the highest, while the coal samples with bedding angles of 30° are the lowest, and the overall distribution is an approximate “U” with the increase in bedding angle. With the increase in bedding angle of 0°–90°, the failure modes of coal samples are tension-shear combined failure, shear-slip failure, and splitting tension failure in turn. (2) The observation of raw coal and CT scanning show that the primary cracks in coal samples are well developed, especially in the lower part of 0° samples, the cracks in 30° samples, and 90° samples are evenly distributed and develop at a certain angle with the weak bedding surface, and microcracks parallel to and nearly perpendicular to the weak bedding surface are developed in 45° samples. At the same time, banded minerals in coal and rock samples are also well developed. (3) The characteristics of crack propagation and evolution in coal samples with different bedding dip angles are significantly different. The bedding dip angles and primary cracks of coal seam have a great influence on crack propagation. With different bedding angles, the propagation modes are different. The crack propagation mainly includes two ways: forming a certain angle with bedding and extending along the bedding plane. (4) The fracture characteristic parameters of coal in the primary state and after failure have the same law with the bedding dip angle, showing a trend of high at both ends and low in the middle, which is an irregular “U”-shaped distribution and has a similar law with mechanical characteristic parameters.

1. INTRODUCTION

At this stage, the development of coalbed methane (CBM) in China is facing great challenges.1 Because of the complicated conditions of coalbed methane development in China, including special terrain, high-rank area, deep coal seam, multiple overlapping of coal seams, symbiotic area of coal seam and coal gas, steep coal seam area, structural area, and coal seam areas, drilling technology is the key to realize efficient development of coalbed methane.2 The development of coalbed methane needs the support of high-tech which is higher than that of conventional gas. Single-well exploitation is the main bottleneck restricting the development of coalbed methane in China. Using the dialectical thinking mode, we can obtain a reasonable coalbed methane development technology.3 Permeability, as an index to measure the allowable fluid passing capacity of porous media, directly affects the selection and design of drilling and completion methods and stimulation measures of coalbed methane wells. Scholars have studied the permeability of steep coal seam and heterogeneous coal samples. The results show that the dip angle of coal seam, fissure, and coal matrix are the main influencing factors of coal seam permeability.4,5 The exploration and exploitation of CBM, an essential unconventional gas resource, have received much attention.6 Most coal reservoirs in China belong to low-permeability reservoirs, which generally need to be reformed by fracturing to form an artificial fracture system to improve the permeability, so as to realize the commercial exploitation of CBM.7,8 Guizhou Province is the largest reserve province of coal resources in the south of China, exceeding the sum of 14 southern provinces, ranking the fifth in coal production in China. Guizhou coal reservoirs also contain a huge amount of CBM, but the development of CBM resources in Guizhou
Province is extremely slow. With the country attaching great importance to coal mine safety and developing clean energy, the research and development investment in coal mine safety and engineering investment of CBM development in Guizhou have increased. However, the coal reservoirs in Guizhou Province have complex structural conditions and reservoir characteristics of low porosity and low permeability, which seriously restrict the development process of CBM resources. The deformation and failure characteristics of coal are the important basis for evaluating the fracturing potential of the coal reservoir and formulating a reasonable fracturing reform scheme.

Coal is a heterogeneous multiphase composite structure material, which contains a large number of randomly distributed natural defects. Its interior is mainly composed of the coal matrix, primary pore defects, and other minerals. The random distribution of these components in the rock determines the internal structural characteristics of the rock, and the complex internal structure of the coal will affect the physical and mechanical characteristics of the coal and the evolution of crack propagation. Analyzing the evolution process from initiation, development, and expansion to penetration of cracks in coal under different bedding angles, and characterizing the evolution characteristics of crack expansion, can help to better understand the failure process of coal, help to further reveal the fracture failure mechanism of coal under different bedding angles, and provide theoretical basis for the evaluation of coal reservoir fracture, efficient exploitation of CBM, and stability evaluation of the coal seam wall.

Scholars at home and abroad have carried out a lot of research work on the evolution law and distribution characteristics of cracks in the process of rock mass fracture. Roslin et al. summarized the development process of technology and equipment in the field of coal damage and reviewed the research progress of coal damage characterization by the CT scanning test. CT imaging technology is often used in combination with mechanical tests to study the evolution characteristics of crack development and expansion in the process of rock re-stressed failure. Gou et al. carried out true triaxial tests and compared the effects of nonreactive fracturing fluid and reactive fracturing fluid on fracture propagation of fractured carbonate rocks, revealing the effects of fracturing fluid types on hydraulic fracture propagation of carbonate rocks. Busse et al. studied the dynamic evolution process of internal cracks caused by deformation and failure of loaded rocks and quantitatively characterized the crack growth during rock fracture using the CT image processing technology and statistical analysis method. Zhao et al. collected CT images of limestone during uniaxial compression failure in real time and converted them into gray histograms using Matlab, so that the damage evolution of limestone during loading can be directly observed. Koudelka et al. used real-time CT testing technology to study the microscopic damage evolution characteristics of gray-green mudstone under disturbance load and obtained CT images and CT values of the rock cross section under different impact disturbance load levels. Yuan et al. studied the development of coal fractures. At the same time, relevant software is used to process CT images, and the box dimension method is used to quantitatively describe the development of coal fractures. Heriawan et al. put forward a crack segmentation method based on contour rotation and gradient direction consistency in order to accurately segment the crack network in the coal CT image sequence and found that this method has higher segmentation efficiency and stronger adaptability. Lv et al. scanned the coal samples during compression by CT and, through processing the original images, revealed the crack evolution characteristics of coal samples at different loading stages. Li et al. processed the CT scanning images of coal using image processing software and established a three-dimensional (3D) model of coal pores and fissures, which can visually observe the distribution and shape of pores and fissures inside coal. Du et al. used CT scanning and 3D reconstruction technology to establish the 3D visualization model of the coal mineral structure and coal assemblage, carried out compression simulation analysis on it, and obtained the damage characteristics and energy evolution law of coal under different compression conditions.

The abovementioned scholars have provided an important scientific basis for the corresponding resource development and engineering construction by analyzing the instability and failure process of rocks and coal with CT scanning observation. However, the geological conditions of coal reservoirs in Guizhou Province are complex, and the research foundation is weak. The multiscale qualitative and quantitative analysis on the evolution characteristics of cracks in coal with different bedding angles of coal reservoirs in Guizhou Province is few, which cannot provide technical support for the commercial breakthrough of CBM exploitation in Guizhou Province.

In this paper, in order to quantitatively describe the propagation and evolution process of internal cracks before and after deformation and failure of coal rocks with different bedding dip angles, the uniaxial loading test and CT scanning test of raw coal were carried out, and the images of raw coal slices scanned before and after loading were vectorized to construct a 3D visualization model of fracture bodies. To quantitatively characterize the dynamic expansion and evolution process of fractures before and after coal fracture, based on the CT scanning stage before and after loading, from whole to local and from macroscopic to microscopic, multiscale statistical analyses of structural characteristic parameters and distribution forms of the fracture network were performed. On this basis, the characteristics of failure morphology along the evolution path of fractures are extracted, and the influence factors of fracture expansion of coal with different bedding angles were revealed. The research results can provide scientific basis for exploring the evolution law of coal fracture and provide theoretical support for scientifically evaluating the safety and stability of CBM mining projects.

2. EXPERIMENTAL DESIGN

2.1. Sample Preparation. The samples used in this study were all taken from the raw coal samples of no 16 coal seam in no 12 Coal Well, Zhijin County, Bijie City, Guizhou Province with a coal seam depth of about 500 m. After the large pieces of raw coal were transported out of the ground, they were quickly wrapped tightly with plastic wrap and then transported to the processing room by boxes with embedded foam boards. The samples were all prepared in the same lump of coal. Coal has strong anisotropy, heterogeneity, and low compressive strength due to the development of many microcracks and micropores. Therefore, in the process of sample preparation, wire-electrode cutting, which has minimal damage, is used for sample processing. The coring direction and some representative samples after processing are shown in Figure 1.
Before the test, the basic parameters of the coal samples were obtained; then, the CT scanning test and the mechanical test were carried out to study the laws of elastic parameters, mechanical parameters, and crack propagation. The basic physical parameters of the coal samples are shown in Table 1. According to Table 1, coal samples have a maximum density of 1.60 g/cm$^3$ and a minimum density of 1.41 g/cm$^3$, and the average density is about 1.45 g/cm$^3$.

### 2.2. Experimental Equipment

The equipment of this experiment includes the uniaxial compression loading system and CT scanning imaging system, as shown in Figure 2. The uniaxial compression loading system was the MTS815 testing machine of the hydraulic servo mechanics system produced by MTS Company of America, with a maximum load of 2800 kN and a maximum confining pressure of 80 MPa. The CT scanning system was the SOMATOM Scope CT scanning system produced by Shanghai Siemens Medical Devices Co. Ltd. The CT scanning system, including the sequential scanning mode and spiral scanning mode, has 24 rows and 16 layers of detectors, which can provide 345 mA X-ray current and 130 kV voltage. In the sequential scanning mode, the continuous scanning in every measuring range is 99 times and the layer thickness is 0.6–19.2 mm. The maximum scanning time of spiral scanning is 100 s, the length is 1530 mm, and the conventional pitch is 0.4–2.0. The axial load internally provided is up to 400 kN, the confining pressure range is 0–20 MPa, and the ambient temperature range is 0–100 °C.

### 2.3. Experimental Methods

At room temperature, a total of 15 coal samples with 5 different bedding angles were used to conduct the uniaxial compression test and CT scanning test. The implementation steps are as follows:

First, the coal samples were scanned by CT to observe their initial pore structure. Coal is loaded by displacement control at a loading rate of 0.05 mm/min. Then, coal samples with

### Table 1. Physical and Mechanical Parameters of Coal Specimens

| specimens   | bedding dip angles (deg) | diameter (mm) | height (mm) | mass (g) | volume (cm$^3$) | density (g/cm$^3$) | peak strength (MPa) | elastic modulus (GPa) | Poisson’s ratio |
|-------------|--------------------------|---------------|-------------|----------|-----------------|--------------------|---------------------|----------------------|-----------------|
| Zj-16-01    | 0                        | 49.86         | 99.88       | 280.52   | 195.01          | 1.44               | 11.57               | 1.64                 | 0.23            |
| Zj-16-02    | 0                        | 49.38         | 99.76       | 285.35   | 191.03          | 1.49               | 12.21               | 1.44                 | 0.20            |
| Zj-16-03    | 0                        | 49.82         | 100.19      | 305.69   | 195.95          | 1.56               | 11.29               | 2.34                 | 0.37            |
| Zj-16-30-01 | 30                       | 49.47         | 99.95       | 277.48   | 192.10          | 1.44               | 5.96                | 1.30                 | 0.18            |
| Zj-16-30-02 | 30                       | 49.50         | 100.07      | 287.67   | 192.59          | 1.49               | 5.70                | 1.00                 | 0.12            |
| Zj-16-30-03 | 30                       | 49.11         | 99.24       | 273.72   | 188.01          | 1.46               | 11.72               | 2.29                 | 0.26            |
| Zj-16-45-01 | 45                       | 49.86         | 100.25      | 279.06   | 195.75          | 1.43               | 14.60               | 2.70                 | 0.22            |
| Zj-16-45-02 | 45                       | 49.32         | 100.24      | 284.48   | 191.51          | 1.49               | 6.13                | 1.58                 | 0.22            |
| Zj-16-45-03 | 45                       | 48.81         | 100.08      | 283.02   | 187.25          | 1.51               | 8.65                | 2.15                 | 0.15            |
| Zj-16-60-01 | 60                       | 49.35         | 100.03      | 270.10   | 191.32          | 1.41               | 17.99               | 3.01                 | 0.20            |
| Zj-16-60-02 | 60                       | 46.40         | 99.90       | 252.09   | 168.94          | 1.49               | 13.44               | 2.58                 | 0.21            |
| Zj-16-60-03 | 60                       | 48.21         | 99.63       | 291.08   | 181.87          | 1.60               | 8.23                | 1.59                 | 0.26            |
| Zj-16-90-01 | 90                       | 49.61         | 100.18      | 286.88   | 193.65          | 1.48               | 16.99               | 3.30                 | 0.38            |
| Zj-16-90-02 | 90                       | 49.49         | 100.16      | 296.18   | 192.68          | 1.54               | 10.59               | 2.18                 | 0.30            |
| Zj-16-90-03 | 90                       | 48.21         | 99.63       | 291.08   | 181.87          | 1.60               | 25.97               | 2.99                 | 0.27            |
different bedding angles were subjected to uniaxial compression tests to obtain their mechanical parameters. Finally, coal samples with different bedding angles were selected for CT scanning again to obtain the damaged pore structure.

3. ANALYSIS OF UNIAXIAL COMPRESSION TEST RESULTS

In order to know the influence of the bedding angle of coal on the mechanical properties of coal in detail, Table 1 is obtained based on the measured data of the abovementioned tests. The following is an analysis and summary of the variation law of peak strength, elastic modulus, and Poisson’s ratio of raw coal samples with different bedding angles.

3.1. Stress—Strain Curve. Different bedding angles reflect the anisotropic characteristics of coal. According to the test data, the stress—strain curve of the sample closest to the average value was selected as the representative, and it was drawn in the same figure, as shown in Figure 3. From Figure 3, first, the stress—strain curve of coal in the uniaxial compression test has an obvious compaction stage, an elastic deformation stage, an unstable failure stage, and a completely unstable failure stage. Second, because the primary cracks of coal are well developed and the individual properties of samples are obviously different, the mechanical parameters of the uniaxial compression test are discrete. Finally, when the stress reaches the peak stress, the coal samples are rapidly destroyed, showing a certain degree of brittleness, but there are differences in the post-peak drop curves, which also show the angle effect of the failure characteristics.

3.2. Mechanical Parameter Characteristics. In the uniaxial compressive test, peak stress, elastic modulus, and Poisson’s ratio are important reflections of strength and deformation characteristics of coal samples. The average values of peak stress, elastic modulus, and Poisson’s ratio of coal samples under uniaxial compression under each bedding angle are obtained by sorting out the data. As shown in Figure 4, the changing trend of mechanical parameters of coal samples with the bedding angle is consistent. When the bedding angle is 90°,

Figure 3. Stress—strain curves of coal.

Figure 4. Relationship between peak strength, elastic modulus, Poisson’s ratio of coal, and bedding dip angle.
the compressive strength of samples is the highest, with an average value of 17.85 MPa, and the lowest value is at 30°, with an average value of only 7.79 MPa. However, the elastic modulus and Poisson’s ratio are the highest at 90°, with average values of 2.82 GPa and 0.31, respectively, and the lowest at 30°, with average values of 1.53 GPa and 0.18, respectively. However, the overall change trend is very similar, and the change trend of compressive strength, elastic modulus, and Poisson’s ratio with the bedding angle is approximately U-shaped.

4. ANALYSIS OF CT SCAN TEST RESULTS OF COAL

4.1. Structural Characteristics and Mechanical Models of Coal with Different Bedding Angles. It is difficult to observe and distinguish the development and distribution of cracks and minerals in coal by ordinary detection equipment. Using the CT scanning system can effectively obtain the internal information of coal samples without damaging the internal structure of the samples. Figure 5a shows the 50th vertical slice of the coal sample with a bedding angle of 90° before loading by CT scanning. From Figure 5a, we can clearly see the weak surface of coal samples, there are long veins in coal, the bedding and near-vertical cracks of raw coal are well developed, and the converted crack density is close to 0.3/cm. Because the mechanical properties of coal are quite different, the coal system will produce different deformations when loaded. The mechanical model of the bedding coal specimen under compression is shown in Figure 5b. From Figure 5b, the upper and lower edges of bedding planes of coal bedding (fragile area of coal body extrusion) are most likely to be damaged, followed by the secondary stress superposition area of coal mass. When the vertical force increases continuously, the stress superposition gradually increases until destroyed, forming penetrating cracks passing through the bedding planes of coal mass, and the damage becomes larger and larger with increasing inclination angle. Here, it is assumed that (1) the strength of coal mass obeys the Mohr-Coulomb criterion and (2) the structural plane of inclined coal mass obeys the Mohr-Coulomb criterion.

As shown in Figure 5b, it is known from Mohr stress circle theory that the normal stress $\sigma$ and shear stress $\tau$ on the bedding plane of coal mass with the bedding dip angle can be calculated from the first- and third-principal stresses:\[\sigma = \frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3)\cos 2\beta\] (1)

For uniaxial compression test

$\tau = \frac{\sigma_1}{2} \sin 2\beta$ (2)

where $\sigma_1$ is the maximum principal stress of the coal bedding plane, $\sigma_3$ is the minimum principal stress, $\beta$ is the angle between the bedding plane of coal bedding and the horizontal plane; and $\sigma$ and $\tau$ are the normal stress and shear stress on the bedding plane, respectively, which will increase with the increase in dip angle. Assuming that the shear strength of the coal bedding plane obeys the Coulomb criterion, there is

$\tau = c + \sigma \tan \phi$ (4)

where $c$ is the cohesion of the coal bedding plane (MPa) and $\phi$ is the internal friction angle (°) of the coal bedding plane, and by combining eqs 1–3, it can be concluded that

$\sigma_1 = \sigma_3 + \frac{2(C + \sigma_3 \tan \phi)}{(1 - \tan \phi \cot \beta)\sin 2\beta}$ (5)

For the uniaxial compression test, $\sigma_3 = 0$, we can obtain

$\sigma = \frac{2C}{(1 - \tan \phi \cot \beta)\sin 2\beta}$ (6)

In eqs 5 and 6, $\phi$ is the internal friction angles of the coal bedding plane, which can be obtained from the Mohr circle and shear-stress envelope curve, and $\beta$ is the intersection angle of the coal bedding plane and horizontal plane. The derived equation is used for the conditions of shear slip failure of coal bedding planes with bedding dip angle under confining pressure. When $\sigma_3 = 0$, it represents the uniaxial compressive strength of coal mass with the bedding dip angle, and bedding shear-slip failure mostly occurs. Because the coal sample contains the bedding and fractured surface, its failure is determined by the corresponding lowest uniaxial compressive strength $\sigma_C$. Therefore, for coal samples with the inclined bedding plane and fractured surface, the failure may be along the bedding shear slip, along the fractured surface shear slip or its mixed mode. This will be explained in detail later.

4.2. Coal Fracture Characteristics. According to the data of the uniaxial compression test and CT scanning, a series of stress–strain curves and CT scanning gray images are obtained, as shown in Figure 6.

It can be clearly seen from the CT scanning gray map of coal samples before and after failure in Figure 6a. During the loading process, a group of X-shaped cracks were produced along the primary cracks in the lower half of the 0° coal sample, and the failure mode of the final sample was mainly shear failure in the lower half, accompanied by more cracks at the lower end. When the coal sample reached the critical stress, the coal failure was characterized by severe failure in the lower part and slight failure in the upper part. From Figure 6b–c, the
Figure 6. Stress–strain and CT scan images of different bedding dip angles: (a) 0°, (b) 30°, (c) 45°, (d) 60°, and (e) 90°.
crack development of 30° and 45° samples mainly produced a single penetrating crack along the bedding direction, which eventually lead to the failure mode of the samples, mainly forming a single failure surface along the bedding surface and shearing failure. It can also be seen from the figure that the peak strain of the sample under these two angles was the smallest, which was due to the weak stress surface along the bedding plane inside the sample. During the stress process of coal samples, the stress surface can be quickly and accurately identified. When the stress reaches the critical value, the interior of the coal sample has already been generated along the fracture zone, so when the coal sample is damaged, it is broken into two blocks along the bedding direction. It can be seen from Figure 6d that when the loading direction and bedding direction make an included angle of 60°, the coal penetrating crack and bedding plane cross the bedding plane at approximately 90°, and the failure mode is mainly single shear failure with a small amount of axial tension splitting. As can be seen from Figure 6e, the cracks in the 90° coal sample develop slowly from top to bottom along the bedding plane layer by layer. When the internal stress of the coal sample reaches the critical value, there are two penetrating cracks in the internal cracks of the coal sample, and the cracks are bifurcated at the upper and lower ends. The failure mode of the coal sample is mainly tensile splitting failure of the vertical bedding plane, accompanied by shear failure at both ends.

From the analysis mentioned above, it can be concluded that there are three main types of failure when the bedding angle of coal gradually increases from 0° to 90°: vertical splitting tensile failure, shear slip failure along the weak bedding plane, and tensile splitting failure through the bedding plane. This is mainly because with the change in angle, the bedding structure and microcracks of coal are compacted, and the influence of stress on coal samples is weakened.

4.3. Analysis of Characteristics of Coal Fracture Expansion and Evolution. In the CT scanning imaging experiment, when X-ray penetrates through the rock specimen, because the internal structure of the rock specimen is composed of mineral components with different densities, the absorption coefficient of X-rays at each point is also different. During the scanning process, the intensity of X-rays attenuates, and the X-ray contains the internal structure density information of the scanned rock specimen. The imaging system receives it and converts it into a digital image, which is convenient to observe the internal structure distribution of the rock specimen. In this paper, the original data are processed and the CT scan slice images are derived. As shown in Figure 7a, in the CT scan image of the rock specimen, the lighter color area is the high-density area mainly composed of mixed minerals, and the black area is the low-density area mainly composed of internal cracks of rocks, in which the gray area is the coal matrix part whose density is between the former.

The 3D visualization image processing software Avizo2019 vectorized the CT slice image stack, used the “Interactive Threshold” module to segment the image threshold to extract the cracks in the image (Figure 7b), and used the “Volume Rendering” module to display the morphology and distribution characteristics of the cracks (Figure 7c). After the above-mentioned series of CT scanning image processing, Table 2 lists the distribution of 3D fractures in coal with different bedding dip angles before and after failure. Subsequently, it will focus on discussing and analyzing the evolution characteristics of cracks in coal with different bedding dip angles.

4.3.1. Qualitative Description of Crack Propagation in Coal. In order to study the dynamic evolution process of crack propagation in the process of coal fracture with different bedding angles, the 3D crack reconstruction of CT scanning slice images before and after fracture was conducted for observation, and the stage qualitative description of crack propagation behavior was made (Figures 6 and 8).
0° specimen: in the initial state, there was a crack in the lower half of the 0° specimen, which was about 40° to bedding. When stress was applied to the specimen for failure, the primary crack was slightly stretched, and a new crack at an angle of about 80° to the primary crack at the lower left of the specimen was produced and became a penetrating crack. When the potential penetrating fracture encountered the primary fracture, the fracture will not pass through the primary fracture, while it will turn around near the end point to generate multiple fractures.

30° sample: as can be seen from the figure, in the initial state, the microcracks of coal specimens were evenly distributed, and some of them extended along the bedding direction. When the specimen was loaded to failure, the crack started from the primary crack and spread along the weak stress plane (bedding plane), and finally, shear slip failure occurred.

45° sample: in the initial state, the microcracks of coal samples were relatively undeveloped, and a few microcracks developed along the bedding direction. When the sample was loaded to failure, the 45° sample had slight slip along the weak bedding surface. When the weak bedding surface reached the ultimate compressive strength, the coal slid directly on the bedding surface, and there was obvious crushing failure at the lower right end of the crack, resulting in vertical cracks.

60° sample: in the initial state, the microcracks in the coal sample were relatively undeveloped, and the microcracks developed at a certain angle with the bedding plane. When the specimen was damaged, the penetrating cracks of 60° developed at an angle of 90° with the bedding plane, and more vertical cracks were produced in the direction of the maximum principal stress.

90° sample: in the initial state, the microcracks in the coal sample were relatively developed, and two potential penetrating cracks with an angle of 80° to the bedding plane were developed on both sides of the sample. During the loading process, the cracks expanded along the primary cracks until destroyed, and the cracks at both ends turned around.

4.3.2. Quantitative Analysis of 3D Fracture Characteristics of Coal. Through the qualitative description and analysis of the crack propagation behavior of coal with different bedding dip angles, the internal crack evolution process of loaded raw coal deformation and failure can be preliminarily understood. In order to deeply study the crack propagation evolution process of coal with different bedding dip angles, the distribution and development of the 3D crack structure in coal were quantitatively analyzed. In this paper, the sphere diameter equal to the crack volume is defined as the equivalent diameter of the crack, which can be calculated using eq 7.

$$D_{eq} = \sqrt[3]{6V_f / \pi}$$

where $D_{eq}$ is the equivalent diameter of the fracture structure and $V_f$ is the volume of the fracture structure.

Fractal dimension is usually used to quantitatively describe the complexity of coal internal structure distribution. The fractal dimension of 3D space of the mineral structure in coal and rock can be obtained using Hausdorff’s capacity dimension (box dimension). The box dimension method is to cover the target set with a cube box with side length $A$, and $N(a)$ is recorded as the minimum number of boxes; then,

$$D = \frac{\log N(a)}{\log a}$$

A series of data about $a-N(a)$ are obtained by covering the target with boxes of different sizes, and then, the relationship between $\log a$ and $\log N(a)$ is fitted by the least square method, and the slope, that is, fractal dimension, is obtained.

Through the “Label Analysis” command module in Aviso2019 software, the structural characteristic parameters of the 3D reconstruction model were obtained (Table 2), including the characteristic parameters such as crack volume $V$, crack surface area $S$, and 3D fractal dimension $D$, among which the crack volume can represent the space occupied by cracks, thus representing the overall damage degree of rock; the surface area of the crack can indicate the extension degree of the crack inside the space; based on fractal theory, the 3D fractal dimension of cracks obtained by box counting method can reflect the chaotic complexity and irregular twists and turns of internal cracks in rocks. The abovementioned characteristic parameter data are drawn in Figure 9, and the changing trend of coal parameters under different bedding dip angles was analyzed. Moreover, the process of crack propagation and evolution was further quantitatively characterized. Figure 9 shows a statistical result curve of characteristic parameters such as internal crack volume $V$, surface area $S$, and 3D fractal dimension $D$ of coal samples with different bedding dip angles before and after fracture, which is analyzed in combination with the distribution information of the internal crack structure of coal samples, in Table 2.

It can be clearly seen from Table 2 and Figure 9 that in the initial state, natural primary defects such as microcracks and...
Microholes are randomly distributed inside the raw coal. With the increase in bedding angle, the crack volume, crack surface area, and 3D fractal dimension in coal first decrease and then increase. Combined with Figure 9 and Table 2, it can be clearly seen that the primary fracture characteristic parameters of 0° and 90° raw coal samples were the largest, and the fracture volume, fracture surface area, and 3D fractal dimension were 86.92 mm³, 503.59 mm², and 1.81, respectively. The cracks in coal under other three angles were small, among which the volume, surface area, and 3D fractal dimension of the cracks were the smallest when the dip angle was 45° and 30°, which are 55.75 mm³, 316.82 mm², and 1.75, respectively. Its changing trend was in good agreement with the 3D fracture model in Table 2 and the CT slice in the initial state in Figure 6. It can be seen from Figure 9 that the volume and surface area of cracks at 0°, 60°, and 90° of the damaged raw coal samples were relatively large, reaching 525.19 mm³, 2708.95 mm², respectively, which was due to the slippage of the sample on the failure surface and the crack growth.

In conclusion, the characteristic parameters of cracks in the initial state and after failure of coal have the same law with the bedding dip angle, showing the trend of high at both ends and low in the middle, showing an irregular “U”-shaped distribution, which has the same law as the mechanical characteristic parameters.

5. DISCUSSION AND APPLICATION

It is found that the influence of the bedding dip angle on the peak strength, elastic modulus, and Poisson’s ratio of raw coal samples is very obvious. With the increase in bedding dip angle, the mechanical parameters of coal show a U-shaped distribution. The failure modes are tension-shear composite failure, shear slip failure, and split tension failure. The change rule of mechanical properties and failure modes of coal with the bedding dip angle can be obtained, which can provide effective technical support for the design of the CBM development project. In addition, it is also found that the bedding and primary fractures of raw coal are the main factors...
affecting the propagation of coal fractures, and the characteristic parameters of coal fractures have obvious laws before and after the failure, especially the laws of 3D fractal dimension of fractures are obvious, and the fractures are well developed after the failure of 0°, 60°, and 90°. The number and complexity of fractures determine the efficiency of CBM exploitation, and the formation mechanism and propagation characteristics of coal fractures with different bedding dip angles are mastered, which is of great significance for large-scale hydraulic fracturing in Zhijin CBM block, Guizhou.

To sum up, the bedding dip angle and primary cracks have great influence on the mechanical properties and crack propagation of raw coal samples. Because the internal structure of coal is complex and the research scope of this paper is limited, further research on the anisotropy of coal and rock and its influence on mechanical properties and crack propagation are needed.

6. CONCLUSIONS

(1) The compressive strength, elastic modulus, and Poisson’s ratio of coal show a strong bedding angle effect, and their changing trends are basically the same. The coal sample with 90° is the highest, with an average of 17.85 MPa, while the minimum value is at 30°, with an average value of only 7.796 MPa, and the change trend is “U” distribution with bedding dip. The failure modes of 0°–90° coal are tension-shear combined failure, shear-slip failure, and splitting tension failure in turn.

(2) Through the visualization model of CT scanning and 3D reconstruction, the shape and distribution of coal fractures in space can be clearly seen. The microcracks in the coal are well developed, especially in the lower half of the 0° sample. The cracks in the 30°, 60°, and 90° samples are evenly distributed and form a certain angle with the bedding, and some cracks in the 45° sample are filled with banded minerals. At the same time, banded minerals are developed in the coal samples.

(3) The evolution of cracks in coal samples with different bedding dip angles is different, and the bedding dip angle of coal and primary cracks has the greatest influence on the crack expansion. With different angles, the expansion mode is different. When the bedding dip angle is 30° and 45°, the fractures mainly extend along the weak bedding plane. The cracks in other angles have unequal angles with the bedding plane and extend through the bedding plane. Fracture expansion mainly includes two ways: forming a certain angle with bedding and expanding along the bedding plane.

(4) The fracture characteristic parameters of coal in the initial state and after failure have the same law with the bedding dip angle, showing a trend of high at both ends and low in the middle. In the initial state, when the dip angle is 30°, the volume, surface, and 3D fractal dimension of the fracture are the smallest. The bedding dip angle is 90°, the fracture volume, surface area, and 3D fractal dimension are the largest. After failure, when the dip angle is 30°, the 3D fractal dimension of the fracture volume and surface area is the smallest. When the dip angle is 60°, the fracture volume, surface area, and 3D fractal dimension are the largest. The general trend is an irregular “U”-shaped distribution, which is similar to the mechanical characteristic parameters.

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Notes

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■ REFERENCES

(1) Li, H.; Lau, H. C.; Huang, S. China’s coalbed methane development: A review of the challenges and opportunities in subsurface and surface engineering. J. Pet. Sci. Eng. 2018, 166, 621–635.

(2) Tao, S.; Pan, Z. J.; Tang, S. L.; Chen, S. D. Current status and geological conditions for the applicability of CBM drilling technologies in China: A review. Int. J. Coal 2019, 202, 95–108.

(3) Tao, S.; Chen, S. D.; Pan, Z. J. Current status, challenges, and policy suggestions for coalbed methane industry development in China: A review. Energy Sci. Eng. 2019, 7, 1059–1074.

(4) Zhang, T. Y.; Tao, S.; Tang, D. H.; Tang, S. L.; Xu, H.; Zhang, A. B.; Pu, Y. F.; Liu, Y. Y.; Yang, Q. Permeability Anisotropy in High Dip Angle Coal Seam: A Case Study of Southern Junggar Basin. Nat. Resour. Res. 2021, 30, 2273–2286.

(5) Men, X. Y.; Tao, S.; Liu, Z. X.; Tian, W. G.; Chen, S. D. Experimental study on gas mass transfer process in a heterogeneous coal reservoir. Fuel Process. Technol. 2021, 216, 106779.

(6) Li, Y.; Chen, J.; Tang, S. H.; Zhang, S. H.; Xi, Z. D. Biogeochemical Assessment of the Coalbed Methane Source, Migration, and Fate: A Case Study of the Shizhuangnan Block, Southern Qinshui Basin. ACS Omega 2022, 7, 7715–7724.
(7) Heng, H.; Liu, X.; Li, X. Z.; Zhang, X. D.; Yang, C. H. Experimental and numerical study on the non-planar propagation of hydraulic fractures in shale. *J. Pet. Sci. Eng.* 2019, 179, 410–426.

(8) Johnson, R. L.; Scott, M. P.; Jeffrey, R. G.; Chen, Z.; Bennett, L.; Vandenborn, C. Evaluating hydraulic-fracture effectiveness in a coal-seam-gas reservoir from surface tiltmeter and microseismic monitoring. *J. Pet. Technol.* 2011, 63, 59–62.

(9) Li, S.; Tang, D. Z.; Pan, Z. J.; Xu, H.; Guo, L. Evaluation of coalbed methane potential of different reservoirs in western Guizhou and eastern Yunnan China. *Fuel* 2015, 139, 257–267.

(10) Puszkarczyk, E.; Krakowska-Madejska, K.-M.; Dohnali, M.; Jelonek, I. Joint analysis using geomechanics, computed X-ray tomography and petrography based on coal samples from a carboniferous basin in Poland. *Build. Eng. Geol. Environ.* 2022, 81, 126.

(11) Roslin, A.; Palajac, D.; Zhou, Y. Cleft structure analysis and permeability simulation of coal samples based on micro-computed tomography (micro-CT) and scan electron microscopy (SEM) technology. *Fuel* 2019, 254, 115579.

(12) Van Stappen, J. F.; De Cock, T.; De Schutter, G.; Cruyded, V. Uniaxial compressive strength measurements of limestone plugs and cores: a size comparison and X-ray CT study. *Build. Eng. Geol. Environ.* 2019, 78, 5301–5310.

(13) Jiang, T. T.; Zhang, J. H.; Wu, H. Experimental and numerical study on hydraulic fracture propagation in coalbed methane reservoir. *J. Nat. Gas Sci. Eng.* 2016, 35, 455–467.

(14) Mathews, J. F.; Campbell, Q. P.; Wu, H.; Halleck, P. A review of the application of X-ray computed tomography to the study of coal. *Fuel* 2017, 209, 10–24.

(15) Gou, B. Z.; Zhan, L.; Guo, J.; Zhang, R.; Zhou, C.; Wu, L.; Ye, J.; Zeng, J. Effect of different types of stimulation fluids on fracture propagation behavior in naturally fractured carbonate rock through CT scan. *J. Pet. Sci. Eng.* 2021, 201, 108529.

(16) Busse, J.; Scheuermann, J. R.; Bringemeier, S. G.; Hossack, D.; Li, A. Image processing based characterisation of coal cleat networks. *Int. J. Coal Geol.* 2016, 16, 1–17.

(17) Liu, W.; Zhang, X.; Fan, J.; Zou, J.; Zhang, Z.; Chen, J. Study on the mechanical properties of man-made salt rock samples with impurities. *J. Nat. Gas Sci. Eng.* 2020, 84, 103683.

(18) Qi, C.; Wang, X. Q.; Wang, J.; Liu, J.; Tuo, J. C.; Liu, K. Y. Three-dimensional characterization of microcracks in shale reservoir rocks. *Petrol. Sci.* 2018, 5, 259–268.

(19) Liu, P.; Ju, Y.; Gao, F.; Pathlegama, G. R.; Zhang, Q. CT Identification and Fractural Characterization of 3-D Propagation and Distribution of Hydrofracturing Cracks in Low-Permeability Heterogeneous Rocks. *J. Geophys. Res.* 2021, 46, 937–949.

(20) Zhao, G. F.; Russell, R. R.; Zhao, X. B.; Khalili, K. Strain rate dependency of uniaxial tensile strength in Gosford sandstone by the Distinct Lattice Spring Model with X-ray micro CT. *Int. J. Solid Struct.* 2014, 51, 1587–1600.

(21) Koudela, P.; Fila, T.; Rada, V.; Zlamal, P.; Sleichtj, J.; Vopalensky, M.; Kumpova, I.; Benes, P.; Vavrik, D.; Vavro, L.; Vavro, M.; Drdacky, M.; Kytyr, D. In-situ X-ray Differential Microtomography for Investigation of Water-Weakening in Quasi-brittle Materials Subjected to Four-point Bending. *Materials* 2020, 13, 1405.

(22) Yuan, M.; Jing, Y.; Armstrong, T.; Mostaghimi, M. Prediction of local diffusion coefficient based on images of fractured coal cores. *J. Nat. Gas Sci. Eng.* 2022, 100, 104427.

(23) Golab, A.; Ward, C. R.; Permana, A.; Lennox, P.; Botha, P. High-resolution three-dimensional imaging of coal using microfocus X-ray computed tomography, with special reference to modes of mineral occurrence. *Int. J. Coal Geol.* 2013, 113, 97–108.

(24) Wang, G.; Qin, X.; Shen, J.; Zhang, Z.; Han, D.; Jiang, C. Quantitative analysis of microscopic structure and gas seepage characteristics of low-rank coal based on CT three-dimensional reconstruction of CT images and fractal theory. *Fuel* 2019, 256, 115900.

(25) Heriawan, M. N.; Koike, K. Coal quality related to microfractures identified by CT image analysis. *Int. J. Coal Geol.* 2015, 140, 97–110.

(26) Ly, Z. X.; Ji, Q. Q.; Ren, W. J. Experimental Study and Percolation Analysis on Seepage Characteristics of Fractured Coal and Sandstone Based on Real-Time Micro-CT; Hindawi, 2020; p 2020.

(27) Zhang, X.; Liu, W.; Jiang, D.; Qiao, W.; Liu, E.; Zhang, N.; Fan, J. Investigation on the influences of interlayer contents on stability and usability of energy storage caverns in bedded rock salt. *Energy* 2021, 231, 120968.

(28) Li, Y. Y.; Cui, H. Q.; Zhang, P.; Wang, D. K.; Wei, J. P. Three-dimensional visualization and quantitative characterization of coal fracture dynamic evolution under uniaxial and triaxial compression based on μCT scanning. *Fuel* 2020, 262, 115685.

(29) Li, C. X.; Nie, B. H.; Feng, Z. W.; Wang, Q. F.; Yao, H. Y.; Cheng, C. L. Experimental Study of the Influence of Moisture Content on the Pore Structure and Permeability of Anthracite Treated by Liquid Nitrogen Freez−Thaw. *ACS Omega* 2022, 7, 7777–7790.

(30) Hao, D. Y.; Tu, S. H.; Zhang, C.; Tu, H. S. Quantitative characterization and three-dimensional reconstruction of bituminous coal fracture development under rock mechanics testing. *Fuel* 2020, 267, 117280.

(31) Li, X.; Li, H.; Yang, Z.; Zou, H.; Sun, W. M.; Li, H. Z.; Li, Y. Coupling Mechanism of Dissipated Energy–Infrared Radiation Energy of the Deformation and Fracture of Composite Coal-Rock Under Load. *ACS Omega* 2022, 7, 8060–8076.

(32) Du, F.; Wang, K.; Zhang, G. J.; Zhang, Y.; Zhang, G. D.; Wang, G. D. Damage characteristics of coal under different loading modes based on CT three-dimensional reconstruction. *Fuel* 2022, 310, 122304.

(33) Zhang, Z.; Jiang, D.; Liu, W.; Chen, J.; Li, E.; Fan, J.; Xie, K. Study on the mechanism of roof collapse and leakage of horizontal cavern in thinly bedded salt rocks. *Environ Earth Sci.* 2019, 78 (10), 292.

(34) Cai, M. F. Rock Mechanics and Engineering; The Science Publishing Company: Beijing, 2013.

(35) Wang, Y. Y.; Teng, Q. Z.; He, X. H.; Feng, J. X.; Zhang, T. R. CT-image of rock samples super resolution using 3D convolutional neural network. *Comput. Geosci.* 2019, 133, 104314.

(36) Ju, Y.; Xi, C. D.; Zhang, Y.; Mao, L. T.; Gao, F.; Xie, H. P. Laboratory In Situ CT Observation of the Evolution of 3D Fracture Networks in Coal Subjected to Confining Pressures and Axial Compressive Loads: A Novel Approach. *Rock Mech. Rock Eng.* 2018, 51, 3361–3375.

(37) Liu, W.; Wang, G.; Han, D. Y.; Xu, H.; Chu, X. Y. Accurate characterization of coal pore and fissure structure based on CT 3D reconstruction and NMR. *J. Nat. Gas Sci. Eng.* 2021, 96, 104242.

(38) Hepling, X.; Zhida, C. Fractal geometry and fracture of rock. *Acta Mech. Sin.* 1988, 4, 255–264.

(39) Tian, W.; Han, N. Evaluation of Meso-damage Processes in Concrete by X-Ray CT Scanning Techniques Under Real-Time Uniaxial Compression Testing. *J. Nondestr. Eval.* 2019, 38, 44.

(40) Ju, Y.; Zheng, J.; Epstein, M.; Sudak, L.; Wang, J.; Zhao, X. 3D numerical reconstruction of well-connected porous structure of rock using fractal algorithms. *Comput. Methods Appl. Mech. Eng.* 2014, 279, 212–226.

(41) Jin, J.; Yang, Z. B.; Qin, Y.; Cui, Y. H.; Wang, G. L.; Yi, T. S.; Wu, C. F.; Gao, W.; Chen, J.; Li, G.; Li, C. L. Progress, Potential and Prospects of CBM Development in Guizhou Province; J China Coal Soc, 2021. https://kns.cnki.net/kcms/detail/11.2190.TD.20211223.1615.004.html.

(42) Vavrik, D. M.; Ryabov, V. B. Fractal dimensions: Computational problems. *USSR Comput. Math. Math. Phys.* 1989, 29, 18–26.

(43) FEI, SAS. Amira-Avizo Software 2019 User’s Guide. Z entnmn fur Infommati onstcel (ZIB), Germany; Thermo Fisher Scientific, 2019.