Mechanical properties and energy development characteristics of impact-prone coal specimens under uniaxial cyclic loading

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ABSTRACT

Energy is the intrinsic driving factor of rock dynamic failure. In this paper, the mechanical properties and energy development characteristics of impact-prone coal are studied. The stress and strain data and the acoustic emission (AE) signals of the impact-prone coal specimens are obtained by conducting cyclic loading-unloading tests. The elastic modulus deterioration rate is defined to describe the deterioration of the mechanical properties of the specimens during the loading process. The calculation results show that the elastic modulus deterioration rate of the impact-prone coal specimens during the cyclic loading process is as low as 3%. The AE monitoring results show that the AE signal is rare in the loading-unloading cycle before failure, and a large number of AE signals are generated at the failure moment. The stress-strain data are used to analyze the energy storage and distribution law of the loading process of impact-prone coal specimens. The results show that the input energy density increases nonlinearly with the increase of the load, and the input energy is mostly stored in the rock as elastic strain energy. The dissipative energy density is linear with the axial load. The impact-prone coal specimens have a strong ability to store elastic energy, and the precursor of damage and failure is not obvious. The study in this paper reveals the cause of the impact-prone coal easily induced to coal bursts from the energy point of view.

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I. INTRODUCTION

Rockbursts are common dynamic disasters in rock engineering. Many scholars in the field of rock mechanics concentrate on solving these dynamic problems (He et al., 2012; Kaiser and Cai, 2012; Konicek et al., 2013; and Feng et al., 2015). In essence, a rockburst is the nonlinear dynamic process of steady energy accumulation and unsteady energy release during the deformation and failure process of a rock system under specific geological conditions (Jiang et al., 2014; 2017). A catastrophic process is an energy evolution process under the combined action of the external load environment, internal structure, and physical-mechanical properties of a rock system. Revealing the energy evolution law of the rock deformation and failure process is beneficial to establish the rockburst criterion based on energy, and the damage law in the rock dynamic failure process can be more realistically reflected (Zhang, 2011).

Studying rock mechanics from the perspective of energy has gained more and more attention in the field of rock engineering. In terms of theoretical analysis, Xie et al. (2005; 2009) proposed that the cyclic loading and unloading process can be used to calculate the elastic energy and dissipative energy during rock failure. Based on this method, Xie proposed the rock energy dissipation mechanism (Xie et al., 2004), rock strength, and overall failure criteria based on the principle of energy dissipation and
release (Xie et al., 2005) and the rock damage evolution equation based on energy dissipation analysis (Xie et al., 2008). These studies provide a way for researchers to study the energy development of rock loading from an experimental perspective. The energy characteristics of rock materials with respect to different loading modes and environmental factors (water, temperature, etc.) are studied. In terms of the loading method, Zhang and Gao (2015) studied the influence of confining pressure on the energy evolution of red sandstone during the loading process, indicating that the confining pressure increased the energy input intensity and weakened the energy release intensity. Li et al. (2017) investigated the energy evolution characteristics of granite specimens under different confining pressures and found that the total strain energy, elastic strain energy, and circumferential strain energy increase with the increase in initial confining pressure. The ratio of dissipative strain energy to total strain energy can be used to describe the extent of deformation and damage of rock specimens during triaxial loading and unloading. Approximately, Peng et al. (2015) selected coal specimens to study their energy dissipation characteristics under different confining pressures. He defined the stress drop coefficient $\alpha$ to describe the evolution of the brittleness mode from brittleness to ductility as the confining pressure increases. The above studies were carried out under the experimental conditions of a low strain rate, while the failure of engineering rock mass mostly occurs under the condition of a high strain rate. For this reason, some people studied the energy development characteristics of rocks under medium or high strain rates. Li et al. (2005) used the Hopkinson pressure bar (SHPB) to conduct impact loading on granite specimens and indicated that the specimens had greater energy absorption and smaller fragments under medium or high strain rates. Jin et al. (2012) studied the dynamic strength and energy development characteristics of sandstones with different axial pressures during cyclic impact loading. As the amount of cyclic impact loading increased, the absorption energy per unit volume increased gradually.

Water-rock interaction is the most frequently considered factor when considering the influence of external factors on the mechanical properties of rock specimens. Guo et al. (2014) investigated the influence of saturated water on the mechanical properties and energy mechanisms of Karst limestone and found that the total strain energy, the releasable strain energy stored before the peak strength, and the increased rate of strain energy under the saturated state are all less than those under the dry state. Similarly, some people carried out cyclic loading and unloading tests on sandstone specimens under natural and saturated conditions and found that saturation reduced the total absorbed energy, dissipative energy, and elastic strain energy of rock specimens (Li et al., 2015; Niu et al., 2018). Temperature is another external factor that affects the energy evolution of rocks. Yin et al. (2013) performed dynamic and static combined loading tests on sandstone specimens at four different temperature levels and found that the energy absorption rate of the rock specimens was simultaneously related to the static load axial pressure and the temperature conducted on the specimens. Wang et al. (2018) investigated the energy dissipation law of six sets of granite specimens treated under different impact loads and found the inverse correlation between the energy dissipation and the processing temperature of the granite specimens. Wang et al. (2017) found that the energy dissipation could reflect the macroscopic fracture characteristics of saturated granite under different low-temperature conditions. Besides, the influences of structural weak surfaces such as bedding and fissures on the energy evolution of rocks were also studied (Liu et al., 2015; Peng et al., 2016; and Li et al., 2018).

Although people have done plenty of studies on the energy development characteristics of rock materials such as sandstone, granite, and limestone, there are few studies on the energy development law of impact-prone coal specimens during the loading process. The impact tendency of coal seams is one of the important conditions for coal bursts. Coal bursts are very common coal mine dynamic disasters in China, which occur with a strong release of energy. Coal bursts are caused by a variety of factors, while the impact tendency of coal is the main internal cause for coal bursts. Therefore, studying the mechanical properties and energy evolution process of impact-prone coal is of great significance for the prevention and control of coal bursts. In this paper, the cyclic loading and unloading tests are carried out on the impact-prone coal specimens, and the acoustic emission (AE) signals of the specimens are monitored synchronously during the tests. The deterioration of mechanical properties, energy development, and AE signal characteristics during the loading process are analyzed. The reason why impact-prone coal is likely to cause coal bursts is revealed from the energy point of view.

II. CALCULATION METHOD OF THE ENERGY OF COAL ROCK LOADING

The deformation process of rocks involves the mutual transformation of various energies, including elastic energy, plastic energy, interface energy, radiant energy, kinetic energy, thermal energy, and gas expansion energy. However, it is difficult to accurately monitor the development process and value of each energy in mechanical tests. On the one hand, the amount of radiant energy released from rock deformation, such as electromagnetic radiant energy, AE energy, and thermal energy, are negligible. It is very difficult to quantitatively monitor the abovementioned radiant energy. On the other hand, the release of the kinetic energy of rock fragments is a transient process, and the instantaneous velocity of these broken rock blocks cannot be accurately determined. If the energy development process before rock failure is considered, the input energy from the loading system mainly evolves into elastic energy and dissipative energy (Zhang and Gao, 2013). The dissipative energy contains plastic energy, interface energy, radiant energy, thermal energy, and gas expansion energy. The total energy input by the loading system ($W$) can be obtained as follows:

$$W = W_e + W_d,$$

where $W_e$ is the elastic energy stored in rock specimens and $W_d$ is the dissipative energy during the loading process.

Dissipative energy is irreversibly released in the form of surface energy, radiant energy, etc., during the loading process. The elastic energy can be stored in rocks during the loading process and released during the unloading process. Xie et al. (2005) proposed the calculation of the mutual transformation of elastic energy and dissipative energy in rocks, according to the rock cyclic loading and unloading process. Figure 1 shows the stress-strain curve of a rock specimen during the loading and unloading experiment. When the strain of the specimen reaches $\varepsilon_s$, the unloading process begins and results...
in an unrecoverable $\varepsilon_0$. The area enclosed by the loading curve and the $\varepsilon$ axis is the total input energy density. The area enclosed by the unloading curve and the $\varepsilon$ axis is the elastic energy density, and the hysteresis loop area between these two curves is the dissipative energy density. The total input energy density ($U_i$), the elastic energy density ($U_{ie}$), and the dissipative energy density ($U_{id}$) can be obtained as follows:

$$U_i = U_{id} + U_{ie}, \quad (2)$$

$$U_i = \int_{\varepsilon_a}^{\varepsilon_b} \sigma \, d\varepsilon, \quad (3)$$

$$U_{ie} = \int_{\varepsilon_a}^{\varepsilon_b} \varepsilon \sigma \, d\varepsilon, \quad (4)$$

where $\varepsilon_a$ is the total strain when the applied stress reaches $\sigma_i$ and $\varepsilon_b$ is the plastic strain when the stress reaches $\sigma_i$.

### III. EXPERIMENTAL DESIGN

#### A. Experimental specimens

To study the energy development characteristics of impact-prone coal, uniaxial cyclic loading and unloading experiments are conducted on the coal specimens collected from the Xinzhouyao coal mine. The Xinzhouyao coal mine located in Datong, Shanxi Province, China, is a mine with frequent coal bursts. The coal seam in the Xinzhouyao coal mine has an impact tendency. Given the important influence of bedding planes on the mechanical properties of coal, the coal specimens are divided into two sets. The specimens in Set A have bedding planes with $90^\circ$, and the specimens in Set B have bedding planes with $0^\circ$. To obtain the characteristics of AE signals during the cyclic loading and unloading process, the whole experimental process was monitored by an AE monitor system.

The coal blocks from the Xinzhouyao coal mine are processed into cylinders with a standard size of $50 \text{ mm} \times 100 \text{ mm}$. Figure 2 shows the experimental specimens. According to the previous test results (Hao et al., 2018), the uniaxial compressive strength of the coal specimens in Set A is about 22.8 MPa, and the uniaxial compressive strength of the coal specimens in Set B is about 44.9 MPa.

#### B. Experimental procedures

The tests are conducted on the MTS815 rock mechanics test system, and the AE signals are monitored by the Express8 equipment developed by Physical Acoustics Corporation (PAC) in America. AE monitoring is used to study the mechanical properties of the impact-prone coal sample during the loading process. The relationship between AE signal characteristics and energy evolution would be further revealed in the future study. The experimental layout is shown in Fig. 3. The loading mode is controlled by axial displacement, and the loading rate is 0.02 mm/min. Two AE sensors ($1#-2#$) are fixed on the cylinder surface of the specimens. To ensure the bonding effect between the AE sensors and the specimens, the contact parts of the sensors and specimens are coated with Vaseline, as shown in Fig. 3.
To obtain sufficient experimental data, reasonable unloading positions need to be designed. If the unloading points are not enough, the experimental data become insufficient, and it will be difficult to analyze the energy development characteristics of the specimens at different stress levels. The objective of the experiment is to obtain about 8–10 sets of loading and unloading curves, which can be used to calculate elastic energy and dissipative energy. The peak load of coal specimens under uniaxial compression loading is about 40–70 kN, so one loading cycle of 5 kN is selected. So the specimens are loaded to 5 kN and then completely unloaded; then, they are loaded to 10 kN completely unloaded again. Every cycle’s load continues to increase until the specimens are completely damaged. The loading process was in the order of $0 \rightarrow 5 \rightarrow 0 \rightarrow 10 \rightarrow 0 \rightarrow 15 \rightarrow 0 \rightarrow 20 \rightarrow 0 \rightarrow 25$ kN, etc.

IV. ANALYSIS OF MECHANICAL PROPERTIES AND AE CHARACTERISTICS

This section reveals the mechanical response characteristics of the impact-prone coal specimens under uniaxial cyclic loading with respect to the characteristics of stress and deformation, bedding effect, and AE signal.

A. Stress and deformation characteristics

The axial strain, lateral strain, and axial stress of the specimens are monitored during the tests. The volumetric strain of the specimens is calculated according to the axial strain and lateral strain, and the relationship between the three strains and axial stress is shown in Fig. 4. It should be noted that the unloading curves of the impact-prone coal specimens in the experiment are very close to the loading curves, and the several loading and unloading curves, as shown in Fig. 4, almost coincided, which resembled a relatively “rough” stress-strain curve. In this part, the characteristics of the mechanical parameters, the deterioration characteristics of the elastic modulus, and the characteristics of the failure modes of the specimens are analyzed.

1. Characteristics of stress and strain parameters

To directly analyze the mechanical properties of the coal specimens in the cyclic loading and unloading process, the mechanical parameters of the specimens are calculated, as shown in Tables I and II.

In Tables I and II, $\sigma$ represents the peak strength, $\varepsilon_a$ is the peak axial strain, $\varepsilon_l$ is the peak lateral strain, $\varepsilon_v$ is the peak volume strain, $\varepsilon_{am}$ is the maximum axial strain, $\varepsilon_{lm}$ is the maximum lateral strain, and $\varepsilon_{vm}$ is the maximum volumetric strain.

Bedding planes have a significant influence on the mechanical properties of the specimens, such as strain, stress, and failure modes. For the strain of the specimens, the specimens with a bedding dip of 90° (A-1 and A-2) have an average peak axial strain of 8.70 × 10⁻³, less than half of that of the specimens with a bedding dip of 0°(18.58 × 10⁻³); the peak lateral strain and volume strain...
are consistent with the peak axial strain; the peak volume strain of the specimens is greater than 0, indicating that the specimens are continuously compressed and the volume is continuously reduced before the peak strength.

From the peak axial strain to the maximum axial strain, the axial strain of coal specimens in Set A increases from $8.70 \times 10^{-3}$ to $9.79 \times 10^{-3}$, an increase of $1.29 \times 10^{-3}$; the axial strain of coal specimens in Set B increases from $18.58 \times 10^{-3}$ to $18.66 \times 10^{-3}$, an increase of only $0.08 \times 10^{-3}$. The lateral strain and volumetric strain from peak to complete failure of Set A increase significantly, the specimens in Set B increases from 18.58 to 9.79, consistent with the experimental results of the uniaxial loading.

From the perspective of the damage mode, several cracks are formed before the final failure of the specimen when the bedding angle is $90^\circ$ (Set A). During the failure process of the specimen, some debris is formed due to splitting. When the bedding angle is $0^\circ$, the specimens rupture along the main plane with a severe damage process, and then the specimens are broken into blocks.

From the peak strength point of view, the peak strength (37.26 MPa) of specimens in Set B is much greater than that in Set A (19.61 MPa). The experimental results of cyclic loading are consistent with the experimental results of the uniaxial loading results.

### 2. Elastic modulus deterioration characteristics

The specimens are accompanied by internal damage during cyclic loading, and these damages can be manifested from the reduction of the elastic modulus. To study the mechanical characteristics of the cyclic loading and unloading process, it is necessary to study the deterioration of elastic modulus of impact-prone coal specimens during the loading and unloading process.

To characterize the change in the elastic modulus of the specimens, the ratio of stress to strain on the stress-strain curve is taken as the elastic modulus value of the specimen. Because of repeated loading and unloading of the specimen, a loading elastic modulus and an unloading elastic modulus can be obtained in each loading-unloading cycle. The elastic modulus obtained in the first loading-unloading cycle is recorded as $E_0$, the elastic modulus obtained in the second loading-unloading cycle is recorded as $E_1$, . . . , and the elastic modulus obtained in the $n$ loading-unloading cycle is recorded as $E_n$. The elastic moduli of the specimens during the cyclic loading process are calculated in Tables III–VI.

It is easy to know that there is no unloading process after the last loading, so the number of the elastic moduli during the loading process is one more than that of the elastic moduli of the unloading process, as shown in Tables III–VI. From these tables, the following two rules of elastic modulus development during the cyclic loading process can be determined. First, during the same loading and unloading cycle, the elastic modulus of the loading process is slightly larger than the elastic modulus of the unloading process. This indicates that certain damage occurs in the loading process of the specimens.

### TABLE I. Parameters of specimens in Set A with bedding dip of 90°.

| Specimen | $\varepsilon_0$ ($10^{-3}$) | $\varepsilon_1$ ($10^{-3}$) | $\varepsilon_v$ ($10^{-3}$) | $\varepsilon_{am}$ ($10^{-3}$) | $\varepsilon_{lm}$ ($10^{-3}$) | $\varepsilon_{vm}$ ($10^{-3}$) | $\sigma$ (MPa) |
|----------|-----------------------------|-----------------------------|-----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------|
| A-1      | 8.79                        | −3.32                       | 2.15                        | 8.93                          | −3.38                        | 2.17                          | 21.86       |
| A-2      | 8.60                        | −3.33                       | 1.94                        | 10.65                         | −14.38                       | −18.11                       | 17.36       |
| Average  | 8.70                        | −3.33                       | 2.05                        | 9.79                          | −8.88                        | −7.97                        | 19.61       |

### TABLE II. Parameters of coal specimens in Set B with a bedding dip of 0°.

| Specimen | $\varepsilon_0$ ($10^{-3}$) | $\varepsilon_1$ ($10^{-3}$) | $\varepsilon_v$ ($10^{-3}$) | $\varepsilon_{am}$ ($10^{-3}$) | $\varepsilon_{lm}$ ($10^{-3}$) | $\varepsilon_{vm}$ ($10^{-3}$) | $\sigma$ (MPa) |
|----------|-----------------------------|-----------------------------|-----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------|
| B-1      | 19.84                       | −7.39                       | 5.07                        | 19.9                          | −10.85                       | −1.81                         | 36.84       |
| B-2      | 17.31                       | −6.83                       | 3.65                        | 17.42                         | −13.01                       | −8.6                          | 37.67       |
| Average  | 18.58                       | −7.11                       | 4.36                        | 18.66                         | −11.93                       | −5.21                         | 37.26       |

### TABLE III. Elastic moduli of A-1 in the cyclic loading process.

| Values         | $E_0$ (GPa) | $E_1$ (GPa) | $E_2$ (GPa) | $E_3$ (GPa) | $E_4$ (GPa) | Average (GPa) |
|----------------|-------------|-------------|-------------|-------------|-------------|---------------|
| Loading        | 1.992       | 1.995       | 1.994       | 1.987       | 1.976       | 1.989         |
| Unloading      | 1.961       | 1.934       | 1.921       | 1.902       | . . .        | 1.930         |
| Average every  | 1.977       | 1.965       | 1.958       | 1.945       | . . .        | . . .          |
TABLE IV. Elastic moduli of A-2 in the cyclic loading process.

| Values          | $E_0$ (GPa) | $E_1$ (GPa) | $E_2$ (GPa) | $E_3$ (GPa) | Average (GPa) |
|-----------------|-------------|-------------|-------------|-------------|---------------|
| Loading         | 1.557       | 1.575       | 1.555       | 1.547       | 1.559         |
| Unloading       | 1.548       | 1.522       | 1.495       | ...         | 1.522         |
| Average of every cycle | 1.553   | 1.549       | 1.525       | ...         | ...           |

TABLE V. Elastic moduli of B-1 in the cyclic loading process.

| Values          | $E_0$ (GPa) | $E_1$ (GPa) | $E_2$ (GPa) | $E_3$ (GPa) | $E_4$ (GPa) | Average (GPa) |
|-----------------|-------------|-------------|-------------|-------------|-------------|---------------|
| Loading         | 1.451       | 1.444       | 1.434       | 1.429       | 1.423       | 1.433         |
| Unloading       | 1.437       | 1.421       | 1.407       | 1.398       | 1.390       | ...           |
| Average of every cycle | 1.444 | 1.433       | 1.421       | 1.414       | 1.407       | ...           |

Second, after each loading-unloading process is completed, the elastic modulus of the specimen during the next loading-unloading cycle is reduced to some extent.

The elastic modulus deterioration rate can be defined using the following equation:

$$\Delta R_E = \frac{E_0 - E_{\text{min}}}{E_0},$$

(5)

where $\Delta R_E$ is the average elastic modulus deterioration rate, $E_0$ is the average elastic modulus in the first loading-unloading cycle, and $E_{\text{min}}$ is the average elastic modulus in the last loading-unloading cycle.

Similarly, the definition of the elastic modulus deterioration rate during the loading process ($\Delta R_{E+}$) is as follows:

$$\Delta R_{E+} = \frac{E_{0+} - E_{\text{min}+}}{E_{0+}},$$

(6)

where $E_{0+}$ is the elastic modulus in the first loading process and $E_{\text{min}+}$ is the elastic modulus in the last loading process.

The definition of the elastic modulus deterioration rate during the unloading process ($\Delta R_{E-}$) is as follows:

$$\Delta R_{E-} = \frac{E_{0-} - E_{\text{min}-}}{E_{0-}},$$

(7)

where $E_{0-}$ is the elastic modulus in the first unloading process and $E_{\text{min}-}$ is the elastic modulus in the last unloading process.

According to the above definition, the elastic modulus deterioration rates of the specimens are calculated as shown in Tables VII and VIII.

The elastic modulus deterioration rate during the cyclic loading process is relatively low, and the average elastic modulus deterioration rate of the two specimens in Set A is only 0.007; for the specimens in Set B, the average elastic modulus deterioration rate during the loading process is 0.020. In contrast, the elastic modulus deterioration rate during the unloading process is slightly higher than that of the loading process. The average elastic modulus deterioration rate during the unloading process of the two specimens in Set A is 0.032, and that of the specimens in Set B is 0.031.

The elastic modulus deterioration rate of the specimens in Set B is larger than that in Set A, indicating that the deterioration of specimens in Set B is more obvious. This is because when the bedding dip is 0°, the bedding plane is parallel to the loading direction, and the pore structure between the specimen layers is more easily compressed and destroyed during the loading process. On the whole, elastic modulus deterioration during the loading and unloading process of the impact-prone coal specimens in the test is not obvious, and the average value of the elastic modulus deterioration rate is less than 0.03. This indicates that the mechanical properties of the coal specimens are almost not weakened. This may be the reason why the failure process of impact-prone coal specimens is severe, and it is easy to cause coal bursts.

B. AE characteristics of experimental specimens

During the loading-unloading process, the internal microcracks are compacted first and then are expanded. Acoustic emission phenomena are closely related to the deterioration of the mechanical properties of the specimens (Sun et al., 2019; Zhang et al., 2019).

TABLE VI. Elastic moduli of B-2 in the cyclic loading process.

| Values          | $E_0$ (GPa) | $E_1$ (GPa) | $E_2$ (GPa) | $E_3$ (GPa) | $E_4$ (GPa) | Average (GPa) |
|-----------------|-------------|-------------|-------------|-------------|-------------|---------------|
| Loading         | 1.847       | 1.842       | 1.824       | 1.825       | 1.815       | 1.831         |
| Unloading       | 1.831       | 1.807       | 1.783       | 1.777       | ...         | 1.800         |
| Average of every cycle | 1.839 | 1.825       | 1.804       | 1.801       | ...         | ...           |
Both the compaction and crack propagation process are accompanied by energy dissipation and AE events. It is feasible to analyze the deformation and damage and energy conversion of the specimen by monitoring the AE signals. Figure 5 shows the AE hit number and the real-time stress value in the same time axis during the tests.

Observing the AE information and stress changes during cyclic loading and unloading of the specimens, the following rules can be found: (1) During the first few cycles of loading and unloading, the specimens release few AE signals. A large number of AE signals are released at the peak strength during the last loading, and the hit number reaches the peak at this time; (2) a small number of AE signals are present in each loading-unloading cycle before failure, and the peak position of these signals is consistent with the stress peak position; and (3) there are also a small number of AE signals during the unloading process, indicating that energy release and energy dissipation occur simultaneously during the unloading process.

V. ANALYSIS OF ENERGY EVOLUTION CHARACTERISTICS

A. Calculation of elastic energy and dissipative energy

It is easy to know from the loading-unloading curve of the specimens that when the coal specimen is loaded to a certain stress level, the unloading curve is slightly lower than the loading curve, and a part of unrecoverable unelastic deformation is generated. The area enclosed between the loading and unloading curves and the strain axis is the dissipative energy density of the specimens. To intuitively reflect and describe the energy development and distribution law of the specimens during the loading-unloading process, the axial stress-strain curve is separately extracted for study.

According to the energy calculation method and experimental data, the experimental data are imported into the ORIGIN software. The input energy density, elastic energy density, and dissipative energy density of the specimens during the uniaxial cyclic loading process are obtained. The results are listed in Tables IX–XII. In the tables, \( u_e \) is the total energy density input by the test machine, \( u_e \) is the elastic energy density, and \( u_d \) is the dissipative energy density. To study the energy dissipation degree of the specimens, the ratio of \( u_d \) to \( u \) is defined as the energy dissipation rate \( R_{ud} \) and the ratio of \( u_e \) to \( u \) is defined as the energy storage rate \( R_{ue} \), as shown in the following:

\[
R_{ud} = \frac{u_d}{u}, \quad (8)
\]

\[
R_{ue} = \frac{u_e}{u}. \quad (9)
\]

B. Energy evolution of the specimens

1. Evolution law of input energy density of the specimens

Figure 6 shows the variation of the input energy density of the specimen as the load increases. In general, the input energy density of the specimens increases with the load, but the whole increase process is nonlinear. The initial input energy density growth rate is low, corresponding to the compaction stage of rock compression; the subsequent growth presents linear characteristics, corresponding to the linear elastic and crack propagation stage of the specimens.

Only 7 and 5 loading-unloading cycles are obtained for A-1 and A-2, respectively. In the five loading and unloading cycles common to A-1 and A-2, the input energy density trends of the two are consistent. The maximum input energy density of A-1 is 0.064 06 MJ/m\(^3\), which occurs when the load is 40 kN; the maximum input energy density of A-2 is 0.042 87 MJ/m\(^3\), which occurs when the load is 30 kN. Although the total input energy density of A-1 is greater than that of A-2, the input energy density of A-2 is significantly greater than that of A-1 at a load level of 30 kN.

Due to the high strength of the specimens B-1 and B-2, 12 and 11 loading and unloading cycles are obtained, respectively. In the first 11 loading and unloading cycles common to both, the input energy density trends of the two are completely consistent. The maximum input energy density of B-1 is 0.172 73 MJ/m\(^3\), which occurs when the load is 60 kN; the maximum input energy density of B-2 is 0.151 38 MJ/m\(^3\), which occurs when the load is 55 kN.

2. Evolution law of elastic energy density of the specimens

The energy input to the specimen is mainly converted into elastic strain energy and dissipative energy. The evolution of elastic strain energy density and dissipative energy density is analyzed in this part.

Figure 7 shows the elastic energy density development of the specimens as the load increases. Comparing with Fig. 6, the elastic strain energy density is very consistent with the input energy density. The elastic energy density curves of the specimens are consistent. The elastic energy density experiences a nonlinear growth in the nonstable stage and a close to steady growth in the linear stage. The similarity between Figs. 7 and 6 is that the energy input to the loader is mostly stored in specimens as elastic strain energy.

3. Evolution law of the dissipative energy density of the specimens

Figure 8 shows the variation in the dissipative energy density of the specimens as the load increases. Comparing the highly uniform...
elast energy density curve shown in Fig. 7, the evolution of the dissipative energy density has the following two characteristics: First, as the axial load increases, the curve of the dissipative energy density of the four specimens is more dispersed. Second, the relationship between the dissipative energy density of a single specimen and the axial load is in a straight line. This shows that the energy dissipation process of a single specimen is more complicated than the energy storage process, and the dispersion of the specimens with the same bedding dip is higher. The density of the dissipative energy increases with the increase of the load during the whole loading process. Also, the specimens do not have significant damage or breakage.

The effect of the bedding angle on the dissipative energy density of the specimen is as follows: (1) Under the same load, the dissipative energy density of the specimens (A-1 and A-2) with a bedding dip of 90° is slightly smaller than that of Set B with a bedding dip of 0°; (2) bedding dip can affect the strength of specimens, which in turn affects the maximum dissipative energy density of the specimens.

C. Energy distribution of the specimens

How the stored energy of the specimen is distributed directly affects the final failure state of the specimens. The essence of energy distribution is shown in Table IX and X.

### Table IX: Energy calculation results of A-1.

| Axial load (kN) | $u_1$ (MJ/m³) | $u_{e1}$ (MJ/m³) | $u_{d1}$ (MJ/m³) | $R_{ue1}$ | $R_{ud1}$ |
|-----------------|----------------|------------------|------------------|-----------|-----------|
| 5               | 0.001 97       | 0.001 40         | 0.000 57         | 0.711     | 0.289     |
| 10              | 0.005 74       | 0.004 93         | 0.000 81         | 0.859     | 0.141     |
| 15              | 0.011 33       | 0.009 98         | 0.001 35         | 0.881     | 0.119     |
| 20              | 0.018 44       | 0.016 82         | 0.001 62         | 0.912     | 0.088     |
| 25              | 0.027 33       | 0.025 28         | 0.002 05         | 0.925     | 0.075     |
| 30              | 0.037 32       | 0.034 78         | 0.002 54         | 0.932     | 0.068     |
| 35              | 0.051 00       | 0.047 57         | 0.003 43         | 0.933     | 0.067     |
| 40              | 0.064 06       | 0.059 92         | 0.004 14         | 0.935     | 0.065     |

### Table X: Energy calculation results of A-2.

| Axial load (kN) | $u_2$ | $u_{e2}$ | $u_{d2}$ | $R_{ue2}$ | $R_{ud2}$ |
|-----------------|-------|----------|----------|-----------|-----------|
| 5               | 0.002 52 | 0.001 88 | 0.000 64 | 0.746     | 0.254     |
| 10              | 0.006 83 | 0.005 80 | 0.001 03 | 0.849     | 0.151     |
| 15              | 0.013 24 | 0.011 72 | 0.001 52 | 0.885     | 0.115     |
| 20              | 0.021 17 | 0.018 88 | 0.002 29 | 0.892     | 0.108     |
| 25              | 0.028 81 | 0.025 83 | 0.002 98 | 0.897     | 0.103     |
| 30              | 0.042 87 | 0.039 41 | 0.003 46 | 0.919     | 0.081     |
distribution is to study the energy storage rate and energy dissipation rate. According to the experimental data, the energy dissipation rate and energy storage rate of the specimens are plotted with the increase of axial load, as shown in Figs. 9 and 10.

1. Development of the energy storage rate

It can be seen from Fig. 9 that the energy storage rate of the specimen increases continuously with the increase of the axial load, and the increase process shows a very strong nonlinear characteristic: the increase rate of the energy storage rate is fast at first. After the load exceeds a certain amount, the increase in energy storage rate gradually slows down. Comparing the energy storage rate curves of specimen B-1 and specimen B-2, the critical load is 20 kN for B-1 specimen and 15 kN for B-2 specimen. It can be seen that the greater the strength of the specimen, the greater the corresponding critical load (B-1) will be; the higher the energy storage rate at the beginning of specimen loading, the lower the corresponding critical load (B-2) will be.

From the development of the energy storage rate, it is clear that the energy storage rate of the impact-prone coal specimens stays at

| Axial load (kN) | u3 (MJ/m³) | u33 (MJ/m³) | u3d3 (MJ/m³) | R_u3 | R_u3d3 |
|----------------|------------|-------------|-------------|-------|--------|
| 5              | 0.00275    | 0.00188     | 0.00087     | 0.684 | 0.316  |
| 10             | 0.00765    | 0.00615     | 0.0015      | 0.804 | 0.196  |
| 15             | 0.01499    | 0.01268     | 0.00231     | 0.846 | 0.154  |
| 20             | 0.02496    | 0.02220     | 0.00276     | 0.889 | 0.111  |
| 25             | 0.03522    | 0.03170     | 0.00352     | 0.9   | 0.100  |
| 30             | 0.04949    | 0.04509     | 0.0044      | 0.911 | 0.089  |
| 35             | 0.06503    | 0.05999     | 0.00504     | 0.922 | 0.078  |
| 40             | 0.08360    | 0.07785     | 0.00575     | 0.931 | 0.069  |
| 45             | 0.10339    | 0.09684     | 0.00655     | 0.937 | 0.063  |
| 50             | 0.12621    | 0.11850     | 0.00771     | 0.939 | 0.061  |
| 55             | 0.14840    | 0.14003     | 0.00837     | 0.944 | 0.056  |
| 60             | 0.17273    | 0.16322     | 0.00951     | 0.945 | 0.055  |

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a high level. Taking B-1 with a lower storage rate as an example, the energy storage rate has reached 0.684 when the load is 5 kN, and since then it has increased with the increase of the load, eventually reaching 0.945. During the whole loading process, the proportion of elastic strain energy is always high and continues to increase.

2. Characteristics of energy dissipation rate variation

As can be seen from Fig. 10, the energy dissipation rate and the energy storage rate change in the opposite direction. The energy dissipation rate of the specimen continues to decrease as the axial load increases. The reduction process also exhibits a nonlinear characteristic: the decrease rate of the energy dissipation rate is relatively fast at first; after a certain load, the decrease of the energy dissipation rate is gradually slowed.

From the development of the energy dissipation rate, it is clear that the maximum energy dissipation rate of the specimen appears in the initial stage of loading, indicating that the energy dissipation effect of the specimen is strong and the energy storage effect is weak during the compaction process. As the load increases, the energy dissipation rate continues to decrease, indicating that the energy storage effect is strong and the dissipation effect is weak at the elastic stage.

Zhang and Gao (2012) studied the energy evolution characteristics of sandstones without impact tendency. The elastic energy ratio of the sandstone specimens is about 82%, which is much smaller than the results of impact-prone coal specimens used in this study (94.5%). Comparing with the energy distribution law of sandstone (Zhang and Gao, 2012), the energy distribution of the impact-prone coal has several points worth noting: (1) the energy storage rate has been maintained at a high level; (2) the maximum energy storage rate is higher than the rock without impact tendency; (3) there is no sign of a sudden decrease in the energy storage rate before the failure of the impact-prone coal specimens. The above characteristics show that the energy storage ability of the impact-prone coal is strong, the precursor of damage or failure is not obvious, and the strong energy release is more likely to occur during the failure process of impact-prone coal. The above study also provides useful suggestions for the prevention of coal bursts in mining engineering, where measures should be taken to weaken the mechanical properties of impact-prone coal, reduce the energy storage capacity of impact-prone coal, and transform the failure mode of the impact-prone coal from a sudden failure mode into a gradual and progressive failure mode. Accordingly, it is preferable to reduce the impact tendency of the coal seam by measures such as coal seam water injection and drilling energy dissipation boreholes.

VI. CONCLUSIONS

In this paper, the cyclic loading and unloading test method is used to comprehensively analyze the stress and deformation characteristics and energy evolution and distribution characteristics of the uniaxial loading process of the impact-prone coal specimens. The following conclusions are obtained:

1. The elastic modulus deterioration rate is defined to describe the reduction of the elastic modulus during the cyclic loading-unloading process. The elastic modulus deterioration rate of the coal specimens with a bedding dip of 0° is more obvious than that of the specimens with a bedding dip of 90°. The elastic modulus deterioration during the loading and unloading process is not obvious, and the average value of the elastic modulus deterioration rate is less than 0.03.

2. The AE monitoring signal indicates that few AE signals are released during the first few cycles of the cyclic loading-unloading process, while a large number of signals are released during the last loading process. Both energy release and energy dissipation occur during the unloading process.

3. The input energy density increases nonlinearly with the increase in the load. Input energy is mostly stored in the rock as elastic strain energy. The dissipated energy density is linear with the axial load. Impact-prone coal specimens have a stronger ability to store elastic energy, so the precursor of damage and failure is not obvious. This is the root cause for this kind of coal to easily cause coal bursts.
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