Characteristics of energy storage and dissipation of coal under one-time cyclic load

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Abstract
Energy is an important research parameter in rock mechanics. To explore the law of energy evolution of coal, a one-time loading and unloading test under uniaxial compression was conducted on coal taken from four different coal mines. By utilizing the area integral method, the total input, elastic, and dissipated energy densities in coal at different unloading levels were calculated. The correlation between various energy densities and the evolution law of energy density with different unloading levels was attained. The peak strengths of the coal slowly declined with an increasing unloading level, which conforms to the relation of a linearly decreasing function. The energy dissipation rate has nonlinear characteristics, and the shape of the dissipation rate fitting curve changed from an upper concave to a downward concave with increasing strength. In all the coal samples, the energy density grew nonlinearly with the unloading level. Moreover, the growth rate of the total energy density was the highest, followed by the growth rates of the elastic and dissipated energy densities. All ratios of the elastic and dissipated energy densities to the total input energy density and the ratio of the dissipated energy density to the elastic energy density were constant. As the strength increased, the input energy and the elastic energy density increased at a faster rate, and they observed the same law. There is an insignificant relationship between the degree of destruction of the coal and the level of unloading. Energy is a major factor that drives the failure of a test piece, but this is not the main factor that determines the degree of damage to the test piece.

KEYWORDS
dissipation rate, energy evolution, linear energy storage, one-time cyclic loads, unloading level
1 | INTRODUCTION

As a primary energy source in China, coal plays a crucial role in the national economy. The shallow underground coal seams are gradually being exhausted, and therefore, mining deep coal seams is imperative. As the mining depth increases, the geological and technical conditions for mining coal become progressively complex, and the mining intensity and difficulty rise. As the mining depth of coal mines and the degree of mechanization increase, the mechanical environment for deep mining becomes extremely complicated and is affected by high geostress, ground temperature, and karst water pressure and strong mining disturbances. In the process of coal mining, owing to periodic disturbances during the excavation and support of a coal seam, the surrounding rock is subjected to a periodic unloading-reloading process that causes frequent major mining difficulties.

The mechanical properties of coal seams under cyclic loading are one of the important factors affecting the safety of coal mines. At present, in rock mechanic tests, the energy analysis method is an important means for investigating rock failure and is fully applied in various fields including rock mechanics and engineering. Theoretical and experimental research has indicated that energy plays an important role in rock deformation and failure. Compared to traditional elastic-plastic mechanical theory, the energy analysis method is irreplaceable in investigating the deformation and failure of rocks. Therefore, on the basis of the proposed macro-meso-micro-system based on energy analysis, studying the law of energy conversion, storage, dissipation, and release inside the rock is very important to prevent coal mine disasters. Many scholars have conducted research and achieved useful results.

Regarding the characteristics of energy evolution of rocks under uniaxial compression, by conducting uniaxial and biaxial compression tests, Xie et al. found that only a small part of the total input energy of rocks is dissipated before reaching the peak strength. The failure process of rocks can be favorably described by utilizing the equation for rock damage and evolution based on energy dissipation. Wang et al. revealed the internal relation between energy changes and confining pressure in the failure process of sandstones by conducting a uniaxial compression test to measure the mechanical parameters of sandstones in the roof of a coal seam. Additionally, the researchers reported the characteristics of energy storage and dissipation in different deformation stages of coal. By conducting a uniaxial compression test on sandstones under loading-unloading conditions, Meng et al. presented the characteristics of energy accumulation, dissipation, and evolution. With the growth of axial stress, the total input energy showed the largest growth rate, followed by the elastic energy, and the growth rate of the dissipated energy was the lowest. Additionally, from the perspective of energy, a series of failure criteria for rocks or indices and methods for stability evaluation based on energy were also put forward.

Regarding research on the energy mechanism of rocks under triaxial compression, Wang et al. conducted an acoustic emission (AE) test on saturated karst limestone in uniaxial and triaxial compressions and analyzed the mechanical properties, AE characteristics, and energy mechanism during rock failure. They concluded that the total strain energy, dissipated energy, and elastic strain energy under peak stress exhibit an exponential relationship with the confining pressure and peak strength of rocks. You et al. and Chen et al. showed a linear relationship between the absorbed energy and confining pressure during rock failure. Moreover, the energy dissipation showed a linear relationship with lateral deformation and a nonlinear relationship with time.

The initial confining pressure and unloading rate significantly influence the transition (accumulation, dissipation, and release) of strain energy. The prepeak absorbed, damage, and elastic strain energies increase with the strain rate; that is, high pressure increases the intensity of the energy input, improves the efficiency of energy accumulation, and inhibits the degree of energy release of rocks. Additionally, Yang et al. analyzed the energy mechanism governing crack propagation by utilizing the energy theory and principle, and put forward the law of energy dissipation and release. They pointed out that with an increase in pressure, the elastic strain energy rises and the dissipated energy density declines linearly.

In the mechanism of the energy evolution of rocks in uniaxial compression under cyclic loading and unloading conditions, Gong et al. selected a variety of rocks for uniaxial compression and loading and unloading tests under different stress levels. Based on the energy consumption characteristics of the entire rock loading process, a linear energy storage method was proposed. Furthermore, a new criterion of rock burst tendency based on law and residual elastic energy index was proposed. Ning et al. conducted a conventional triaxial compression test, triaxial compression test under cyclic loading-unloading conditions, and AE test on coal samples buried 980 m deep. They suggested that the change in the dissipation rate of prepeak energy conforms to coal failure and that the threshold value of initiating cracks is positively proportional to the peak stress. Based on a Brazilian test, point load test, and semicircular bending test for marble, Peng et al. and Gong et al. analyzed the characteristics of the total, elastic, and dissipated energy during the tensile failure of rocks, thus determining their interrelations.

The above research showed that scholars have made remarkable achievements in determining the characteristics of energy evolution of coal under uniaxial compression, triaxial compression, and cyclic loading and unloading. However, a majority of the research focused on characterizing the evolution process of energy, while research on quantitatively...
characterizing the relationships of the input, elastic energy, and dissipated energy densities of coal at different unloading levels is still insufficient. By employing an MTS test system, four types of coal were subjected to a one-time loading and unloading test under uniaxial compression. On this basis, the quantitative relationships of the elastic and dissipated energy densities with the total input energy density and that between the dissipated and elastic energy densities were explored. Moreover, the law of the dissipation rate of energy at different unloading levels and the influence of different unloading levels on the peak strength of the samples during failure were analyzed. This research revealed the failure characteristics of coal from the perspective of energy, providing theoretical support for illustrating the mechanism of coal failure.

2 | EXPERIMENTAL SYSTEM AND PROCEDURES

2.1 | Coal samples and experimental system

Coal obtained from four different coal mines were used for the test. The coal samples were processed into cylinders with the specification of Φ50 mm × 100 mm and were ground to guarantee that the perpendicularity and parallelism of the samples conform to the rules of rock mechanics. The four types of coal from different coal mines were categorized as Class A, Class B, Class C, and Class D according to their strength (Figure 1). The parameters are listed in Tables 1 and 2. After the samples were numbered, three samples were randomly taken from each type for conventional uniaxial compression tests, and then, the average value of their compressive strengths was measured as the estimated compressive strength of the loading and unloading samples σc (for the convenience of setting different unloading levels in a subsequent test).

An MTS electrohydraulic servo-controlled test system allowing combined tension and torsion was applied in the test. The system with stable performance can be utilized in various tests (such as uniaxial compression, cyclic loading and unloading, and tension-torsion loadings) under complex stress conditions. The axial load capacity of the system is ±100 kN, and the measurement accuracy of the load and displacement is ±0.5% of the indicated value. By utilizing the test system, diverse parameters (including the tensile strength, compressive strength, yield point, and Poisson’s ratio) can be accurately and rapidly measured. The test system with an accuracy level of 0.5 works in different loading modes, including displacement and stress control. Given the laboratory conditions, the equipment can operate steadily for a long time. Figure 2 displays the one-time loading and unloading test system.

2.2 | Experiment protocol and steps

The test was conducted in two stages: conventional uniaxial compression and single-axis one-time loading and unloading tests. First, according to the compressive strength σc of the coal body, different unloading levels (20% σc, 40% σc, 60% σc, and 80% σc) were set to perform an unloading test, and the loading was performed after loading to a preset unloading level. The true unloading level is the ratio of the peak strength to the actual stress value at the unloading level. As the coal body has a hysteresis effect during the unloading process, it cannot be unloaded to 0 when unloading, and the minimum unloading level was set for the four kinds of samples; that is, after unloading to 2% σc, the loading was performed until the sample was destabilized.

Considering the viscoelasticity of coal, and as the stress-strain curve of loading and unloading can be accurately measured once, the loading mode was selected as the displacement control. The loading rate was 0.1 mm/min, and the
The true unloading level is the ratio of the peak strength to the actual stress value at the unloading level.

The area between the initial loading curve and the horizontal axis is the total input energy density (the total input energy at the unloading level is equal to the input energy density multiplied by the sample volume), and the area between the unloading line and the horizontal axis is the elastic energy density (unloading). The total elastic energy at this level is equal to the elastic energy density multiplied by the sample volume. By integrating the stress-strain curves at different unloading levels \( \sigma_c \), specific values of the total input energy density, elastic energy density, and dissipated energy density can be obtained. Figure 4 shows the calculation of energy density at the unloading point.

### RESULTS

#### 3.1 Uniaxial compression test

Before conducting a one-time loading and unloading test, the compressive strengths of different samples were determined through a conventional uniaxial compression test, and the average compressive strength was calculated to determine the unloading level. Figure 5 shows the stress-strain curves of the four types of coal under uniaxial compression.

Each type of coal was subjected to compaction, elastic, plastic, and failure phases in accordance with their stress-strain curves. The same type of coal showed diverse strengths, which were mainly determined by the properties of the coal. As coal belongs to a heterogeneous body which has a large number of fractures, cracks, and joints, the strength of coal samples obtained from different deposits of the same type of coal was different. Figure 5 shows that Class C coal does not have an inconspicuous elastoplastic stage (after the stress exceeds the yield stress, the stress-strain curve is concave...
as the stress increases, showing a strain increase phenomenon, and Class A, Class B, and Class D coals have relatively evident elastoplastic stages. The stress-strain curves of the four coal samples have a sawtooth shape, which is related to the coal’s own properties. Before the peak strength, the coal sample experienced a coal piece collapse. After the peak strength, except for the A-type coal body, there was no ejection phenomenon, and the other three kinds of coal exhibited the phenomenon of coal piece ejection. The four types of coal were subjected to a conventional uniaxial compression test to further determine the corresponding basic mechanical parameters. Table 1 shows the basic mechanical parameters of coal samples. Table 2 shows industrial and elemental analyses.

3.2 | One-time loading and unloading test

After conducting a uniaxial compression test, the compressive strength of each type of coal was calculated. According to the obtained average compressive strengths of each sample, a one-time loading and unloading test with different unloading levels was conducted. Four unloading levels were set for each type of coal in which the minimum and the maximum unloading levels were 0.2 $\sigma_c$ and 0.8 $\sigma_c$, respectively. Four different unloading levels were likely to be seen in the compaction, elastic, and elastic-plastic phases of the stress-strain curve.

To compare and analyze the results, the stress-strain curves of the four coal samples with unloading levels of 0.2 $\sigma_c$, 0.4 $\sigma_c$, 0.6 $\sigma_c$, and 0.8 $\sigma_c$ were combined at first, as shown in Figure 6. As shown in the figure, in the one-time loading and unloading test under uniaxial compression, the loading curve did not coincide with the unloading curve, showing a hysteresis loop. This indicated that energy dissipation occurred in the loading and unloading process. Additionally, the hysteresis loops of the four coal samples were shaped like a crescent in the stress-strain curve of one loading and unloading. Among the four coal samples, the strength of A was the smallest, but the shape of its hysteresis loop was the most evident. The other three types of coal were stronger, but their hysteresis shapes were not very clear. This indicates that during the loading and unloading process, the strength of coal is different, and the degree of energy dissipation is also different.

The elastic modulus of the rock material reflects the resistance of the rock to deformation under the condition of stress. At the same time, the modulus can also be reflected in the initiation, expansion, and connection process of cracks in the material to some extent. Therefore, changes in the
elastic modulus help to understand how cyclic loading affects rock material deformation. To better describe the hysteresis loop, based on the data recorded in each cycle during the experiment, the elastic modulus for each loading and unloading was calculated according to the calculation principle shown in Figure 7 and the following formula:

\[
E_L = \frac{0.6\sigma_c - 0.4\sigma_c}{\varepsilon_{0.6i} - \varepsilon_{0.4i}} 
\]

(1)

\[
E_U = \frac{0.6\sigma_c - 0.4\sigma_c}{\varepsilon_{0.6i} - \varepsilon_{0.4i}} 
\]

(2)

where \(E_L\) is the loading elastic modulus (MPa); \(E_U\) is the unloading elastic modulus (MPa); \(\varepsilon_{0.6i}\) is the strain corresponding to the loading phase \(0.6i\sigma_c\); \(\varepsilon_{0.4i}\) is the strain corresponding to the loading phase \(0.4i\sigma_c\); \(\varepsilon_{0.6i}\) is the strain corresponding to the unloading phase \(0.6i\sigma_c\); and \(\varepsilon_{0.4i}\) is the strain corresponding to the unloading phase \(0.4i\sigma_c\).

Table 3 is the calculation result of elastic modulus. Figure 8 shows that the loading elastic modulus of each type of coal is smaller than the unloading elastic modulus. At the same time, the loading and unloading elastic moduli have the exact same trend. Taheri et al.\(^{41}\) and Peng et al.\(^{38,39}\) studied the tangential elastic modulus of 50% of the loading amplitude. Compared with their research conclusions, we found that the elastic modulus does not increase with an increase in the unloading stress level. The relationship between the loading and
unloading elastic modulus and the actual unloading level was not observable. In addition, some researchers used the secant elastic modulus and other forms of the elastic modulus as analysis and evaluation indicators.42,43

### 3.3 Failure characteristics of coal samples

Figure 9 displays the failure characteristics of the four types of coal samples during a one-time loading and unloading test under uniaxial compression. (a) Class A coal samples with rough surfaces, large particle sizes, and many gaps and cracks between the particles showed the lowest average strength among the four types of coal samples. During compression-inducing failure, no spalling phenomenon appeared. A low bursting sound and rapid damage velocity were observed, and the surfaces of particles were bright. (b) Class B coal samples with smooth surfaces exhibited a small number of surface microcracks and more microfractures. During the compression-inducing failure, the spalling phenomenon occurred, and the coal samples were broken into large blocks while exhibiting a low overall damage degree. (c) Class C coal samples, similar to Class B ones, presented an average strength lower than that of Class D coal samples and had the approximate strength of Class B coal samples. During the failure, the spalling phenomenon and a loud bursting sound appeared, with a low damage velocity and flaky damaged coal. (d) Class D coal samples with extremely smooth and fine surfaces had a high average strength. There were a small number of fractures on the surface of the coal samples, and
the media were tightly connected. During the failure of the coal samples, significant spattering of coal dust occurred with loud bursting sounds, and the damaged coal samples mainly appeared in a flaky shape. The four types of coal samples were intensively subjected to tensile and shear failure.

3.4 Relationship between peak strength and unloading levels

Figure 10 displays the relationship between the peak strengths of the four types of coal samples during the one-time loading and unloading test, and their unloading levels. According to classical rock mechanic theory and the existing rock mechanic experimental results, the peak strength of some brittle rocks increases with an increase in the number of loadings and unloadings under cyclic loading and unloading conditions. That is, the rock will show strengthening under cyclic loading and unloading conditions. The rock peak strength will increase. However, in this one-time loading and unloading test of four types of coal, the coal did not show a strengthening phenomenon but instead had a "strength weakening" phenomenon.

There are many reports on the phenomenon of peak strength enhancement of uniaxial cyclic loading and unloading rock, but there are also many studies on peak strength weakening of rock under uniaxial cyclic loading and unloading. For example, Eberhardt et al.44 conducted a uniaxial cyclic loading and unloading experiment on the Pink Lac du Bonnet of the buried underground cavern URL. It was found that the peak strength of uniaxial cyclic loading and unloading of most rock samples was significantly smaller than that under uniaxial compression. Intensity, that is, peak strength weakening, occurs. Zhou et al.45 conducted a uniaxial cyclic loading test on sandstone. It was found that the cyclic loading and unloading strength of sandstone is much lower than that of uniaxial compression.

The peak strength of the uniaxial cyclic loading and unloading of brittle rock is affected by many factors. It can be seen from Figure 10 that as the level of unloading increases, the destructive strength of the coal body shows a significant slow decreasing trend, that is, the unloading level increases and the strength decreases slightly. Dissipative energy and disturbances have a greater impact on coal damage during the loading process. As a result, cracks are formed, and microcracks increase and penetrate, eventually leading to a decrease in the strength of the coal body. However, the degree of

| Specimen ID | γ  | Loading elastic modulus (MPa) | Unloading elastic modulus (MPa) |
|------------|----|-------------------------------|-------------------------------|
| AJ-1-1     | 0.1983 | 890.85                        | 1217.33                       |
| AJ-1-2     | 0.3989 | 1305.39                       | 1699.19                       |
| AJ-1-3     | 0.6059 | 978.19                        | 1304.26                       |
| AJ-1-4     | 0.8271 | 1447.31                       | 1872.79                       |
| BJ-1-1     | 0.1982 | 1282.14                       | 1456.41                       |
| BJ-1-2     | 0.4048 | 1320.81                       | 1544.05                       |
| BJ-1-3     | 0.6609 | 1658.06                       | 1763.80                       |
| BJ-1-4     | 0.9140 | 1321.54                       | 1508.40                       |
| CJ-1-1     | 0.1955 | 1808.76                       | 1912.64                       |
| CJ-1-2     | 0.3945 | 2373.41                       | 2413.77                       |
| CJ-1-3     | 0.6104 | 1985.31                       | 2065.03                       |
| CJ-1-4     | 0.8264 | 1647.68                       | 1731.17                       |
| DJ-1-1     | 0.1798 | 1890.16                       | 1890.98                       |
| DJ-1-2     | 0.4061 | 2024.43                       | 2152.82                       |
| DJ-1-3     | 0.6461 | 1809.87                       | 1889.88                       |
| DJ-1-4     | 0.8856 | 1612.34                       | 1701.20                       |

FIGURE 7 Principle of elastic modulus calculation

FIGURE 8  Loading and unloading elastic modulus
FIGURE 9  Failure characteristics of four types of coal during a one-time loading and unloading test. (A), (B), (C), and (D) separately correspond to Class A, Class B, Class C, and Class D coal samples.
weakening of different coal bodies can vary: Some are more evident, and some are weaker. The Class D coal presented the largest average strength and the largest reduction rate of the peak strength during failure in the one-time loading and unloading test. Moreover, Class A coal exhibited the lowest average strength and reduction rate of the peak strength. Class B and Class C coal showed an approximate average strength, and their reduction rates of peak strength were also basically consistent.

### 3.5 Relationship between dissipation rate and unloading levels

Based on the stress-strain curves, according to different unloading levels set in the test, the total input, elastic, and dissipated energy densities at different unloading levels can be calculated by utilizing the area integral method. The energy density can be calculated by using following formulae:\(^{(3)}\)

\[
U = U^e + U^d
\]

\[
U = \int_0^{\varepsilon_1} \sigma \, d\varepsilon
\]

\[
U^e = \int_0^{\varepsilon_1} \sigma \, d\varepsilon
\]

Based on the above formulae, Table 4 displays the total input, elastic, and dissipated energy densities, dissipation rates, and peak strengths of the four types of coal at different unloading levels.

The dissipation rates corresponding to different unloading levels were subjected to curve fitting. The dissipation rate is defined as the ratio of the dissipated energy density to the total input energy density. It can be seen from the curve in Figure 11 that the dissipated rates of the four coal samples all have nonlinear characteristics. The fitting curve of Class A coal is special, the curve is convex, and the dissipation rate increases first and then decreases. When the true unloading level is 0.3989 (the actual unloading level is in Table 2), the

![Figure 10](image)

**Figure 10** Relationship between different unloading levels and peak strength under a one-time loading and unloading condition

| Coal specimen | Specimen ID | $\gamma$ | $U$ (mJ mm\(^{-3}\)) | $U^d$ (mJ mm\(^{-3}\)) | $U^e$ (mJ mm\(^{-3}\)) | $\eta$ | Peak strength (MPa) |
|---------------|-------------|--------|-----------------|-----------------|-----------------|------|--------------------|
| A AJ-1-1      | 0.1983      | 0.00165| 0.00048         | 0.00117         | 0.28826         | 9.2061|
| AJ-1-2        | 0.3989      | 0.00626| 0.00244         | 0.00382         | 0.38978         | 9.1548|
| AJ-1-3        | 0.6059      | 0.01198| 0.00330         | 0.00868         | 0.27546         | 9.0403|
| AJ-1-4        | 0.8271      | 0.01652| 0.00512         | 0.01140         | 0.30993         | 8.8301|
| B BJ-1-1      | 0.1982      | 0.00735| 0.00158         | 0.00577         | 0.21480         | 16.1732|
| BJ-1-2        | 0.4048      | 0.01346| 0.00211         | 0.01135         | 0.15706         | 15.8342|
| BJ-1-3        | 0.6609      | 0.02803| 0.00223         | 0.02580         | 0.07963         | 14.5484|
| BJ-1-4        | 0.9140      | 0.05039| 0.00691         | 0.04348         | 0.13715         | 14.0253|
| C CJ-1-1      | 0.1955      | 0.00394| 0.00043         | 0.00351         | 0.10838         | 17.6027|
| CJ-1-2        | 0.3945      | 0.01290| 0.00106         | 0.01184         | 0.08191         | 17.4442|
| CJ-1-3        | 0.6104      | 0.03059| 0.00340         | 0.02719         | 0.06715         | 16.9095|
| CJ-1-4        | 0.8264      | 0.05287| 0.00518         | 0.04769         | 0.09798         | 16.6534|
| D DJ-1-1      | 0.1798      | 0.00501| 0.00033         | 0.00468         | 0.06567         | 23.6454|
| DJ-1-2        | 0.4061      | 0.02042| 0.00175         | 0.01867         | 0.0857          | 20.9415|
| DJ-1-3        | 0.6461      | 0.04405| 0.00268         | 0.04136         | 0.06073         | 19.7470|
| DJ-1-4        | 0.8856      | 0.07777| 0.00781         | 0.06996         | 0.10039         | 19.2065|
dissipation rate is the highest. The wear rate fitting curves for Class B, Class C, and Class D coals are opposite to those of Class A, and the curve is concave. For B coal and C coal, the true unloading level is 0.19820 and 0.1955, respectively, the dissipation rate is the highest, and the dissipation rate first decreased and then increased.
The dissipation rate exhibits nonlinear characteristics because it may be affected by its own properties, strength, and internal structural changes during loading and unloading. It can be seen from Table 1 that the compressive strengths of the four types of coal are \( A < B < C < D \), the shape of the fitting curve of the dissipation rate changes from a convex shape to a concave shape with increasing strength, and the shape opening degree becomes larger and larger. The irregularity of the dissipation rate also reflects the integrity of the sample from the side. The greater the dissipation rate, the more defects in the sample, and the more complex the internal variation of the sample during the loading and unloading process. The fitted curves of the dissipation rate of the four coals show that A has more obvious specificity, and its curve is opposite to the direction of the curves of the other three coals. It is known that the magnitude of intensity has a certain effect on the convex shape of the fitted curve. Simultaneously, due to the lower strength of A, its internal structure is more complicated, and some of its characteristics also have a certain impact on the convex shape of the fitted curve.

### 4 | DISCUSSIONS

#### 4.1 | Nonlinear evolution law of internal energy of coal samples during a one-time loading and unloading test

According to the calculated energy densities at different unloading levels, the relationship curves of the total input, elastic, and dissipated energy densities of the four types of coal with unloading levels can be drawn.

It can be seen from Figure 12 that the total input, elastic, and dissipated energy densities of the four types of coal all nonlinearly rise with unloading level, that is, the energy evolution showed a nonlinear characteristic that can be favorably fitted by using a quadratic function. The law of energy storage obtained in the test favorably matched the research results of You et al.\(^{27}\) and Gong et al.\(^{33,37}\) Table 5 lists the correlation coefficients of the 12 function curves. The minimum value is 0.88110 and the maximum value is 0.99994, which indicates that the quadratic function relationship can well describe the nonlinear growth trend of the energy density, indicating that the coal is in the uniaxial compression process. The internal energy evolution mechanism has nonlinear characteristics. Based on the relationship curve between the energy density and unloading level, the dissipated energy density displayed the lowest growth rate with the unloading level, followed by the elastic energy density, and the total input energy density showed the greatest growth rate.

The four curves exhibited a significant characteristic: With an increase in the unloading level, the differences in the total input, elastic, and dissipated energy densities at two adjacent unloading levels gradually rose, that is, the distance between the adjacent two points increased. Additionally, the curves of the elastic energy densities of Class A, Class B, Class C, and Class D coals were highly consistent with their curves of total input energy density but deviated from their curves of dissipated energy density. The main reason was that the energy stored in the samples mostly appeared as elastic energy, that is, the elastic energy accounted for a large proportion, while the proportion of the dissipated energy was relatively low. In conclusion, as the strength became higher, more elastic energy was stored in the samples, and there were more similarities between the elastic and the total input energy densities. Thus, the higher the proportion of the elastic energy density, the greater the released kinetic energy and the higher the damage degree.
4.2 Linear law of energy storage of different types of coal

The previous section discussed the change laws of the total input, elastic, and dissipated energy densities of the four types of coal with changing unloading levels. In this section, the relationships of the elastic and dissipated energy densities to the total input energy density and that between the dissipated and the elastic energy densities are separately taken into account. These relationships were separately subjected to linear fitting. According to different unloading levels, scatter diagrams of the elastic and dissipated energy densities separately with the total input energy density and that between the dissipated and the elastic energy densities were drawn. It can be clearly seen from Figure 13 that there was a significant linear relationship between the elastic and the total input energy densities of the four types of coal.

The growth trends of the four curves were basically consistent. Similarly, the dissipated energy density exhibited a strong linear relationship with the total input and the elastic energy densities of the four types of coal. As shown in Figure 13, the fitting degree between the elastic and the total input energy densities was the highest and had the largest slope, followed by the fitting degree between the dissipated and total input energy densities. The lowest fitting degree occurred between the dissipated and elastic energy densities. It was implied that the total input energy mainly appeared as the elastic energy, while the proportion of the dissipated energy was relatively low. The relationship curve between the energy density and the unloading level supported this result.

FIGURE 13 Relationships between elastic and total input energy densities. (A), (B), (C), and (D) correspond to Class A, Class B, Class C, and Class D coal samples
Figures 14 and 15 also exhibit a significant characteristic: The two figures show approximated fitting degrees and slopes of the curves, and the fitting points were located at basically consistent positions on two sides of the fitting curves in the two groups of figures. The main reason leading to this phenomenon was that the elastic energy density approximated the total input energy density, and therefore, the ratios of the dissipated energy density to the two were basically equivalent.

It can be seen from Figures 13-15 that the fitting curves of the elastic and dissipated energy densities with the total input energy density and those between the dissipated and elastic energy densities all satisfied the relation of the linear function.

\[ U^e = \alpha U + k_1 \]  
\[ U^d = \eta U + k_2 \]  
\[ U^d = \beta U^e + k_3 \]

where \( \alpha, \eta, \beta, k_1, k_2, \) and \( k_3 \) are constants. Moreover, \( k_1, k_2, \) and \( k_3 \) are about three magnitude orders lower than \( \alpha, \eta, \) and \( \beta, \) and thus, they can be ignored. In this context, the fitting curves of the elastic and dissipated energy densities with the total input energy density and that between the dissipated and elastic energy densities approximately satisfy the relation of the linear function.

\[ U^e = \alpha U \]  
\[ U^d = \eta U \]  
\[ U^d = \beta U^e \]

**FIGURE 14** Relationships between dissipated and total input energy densities. (A), (B), (C), and (D) correspond to Class A, Class B, Class C, and Class D coal samples.
By analyzing the above formulae, the ratios of the elastic and dissipated energy densities to the total input energy density and that of the dissipated energy density to the elastic energy density were all constants. $\alpha$ refers to the coefficient of energy storage, which represents the capacity of the samples for storing energy. This result conforms to the conclusion by Gong et al.\textsuperscript{26} The larger the energy storage coefficient, the stronger the rock’s ability to store energy, and vice versa. Having a high energy storage coefficient can solve the problem related to the increase in the unloading time of the testing machine that occurs when the rock sample is at the peak strength. The elastic energy at the peak strength point can then be obtained. Similarly, $\eta$ is defined as the energy dissipation rate, that is, the ratio of the dissipated energy density to the total input energy density during the sample loading process. This coefficient represents the ability of the rock material to consume energy. The larger the energy consumption coefficient, the stronger the rock’s ability to consume energy, and vice versa. In addition, the experimental results show that there is also a linear relationship between the elastic energy density and the dissipated energy density. This relationship also reflects the ratio of the dissipated energy density to the elastic energy density, which is expressed by $\beta$. In this study, we chose four kinds of coal with different strengths as test samples. Based on the experimental results and the change law of the three coefficients, we can consider the selected samples as universal. Studying these three coefficients has certain practical significance and can provide an important reference for researching or predicting disasters such as rock burst and coal burst.

**FIGURE 15** Relationships between dissipated and elastic energy densities. (A), (B), (C), and (D) correspond to Class A, Class B, Class C, and Class D coal samples.
4.3 Quantitative and qualitative analysis of failure characteristics

To better show the differences between the four types of coal, we combine and analyze the results of the coal type characteristics, damage characteristics, and energy density calculations. Combining the total input energy density, elastic energy density, and dissipated energy density of the four coal samples, we obtain Figure 16. Combining Table 1 and Figure 16 clearly shows that as the strength increases, the input energy density and elastic energy density increase at a faster rate, and they have the same law. The difference is that the change law of the dissipated energy density with intensity is not very evident. As shown in Figure 16C, the energy input and the storage of elastic energy are related to the strength of the coal. The greater the intensity, the more elastic energy is stored. It can be known from Tables 1 and 2 that the compressive strengths of the four coal samples are different, and their elemental analyses are also different.

By comparing and analyzing Figures 9 and 16, it can be seen that the damage degree of Class A coal is the largest at the second and third unloading levels, the damage degree of Class B coal increases with an increase in the unloading level, and the damage degree of Class C coal is basically the same at each unloading level. The rules of the damage degree of D-type coal and B-type coal are similar and increase with an increase in the unloading level. Based on the combined damage characteristics of the four types of coal, it can be observed that the damage degree of Class B coal is the smallest, but the block size is the largest. Combined with Section 3.3, it can be seen that the relationship between the damage degree of coal and the unloading level is not very palpable. Energy is an important factor driving the failure of the test piece, but it is not the main reason that determines the degree of damage to the test piece.

**FIGURE 16** Comparison of energy density of four coal samples
5 | CONCLUSIONS

Energy conversion invariably occurs during the compression-inducing failure of the samples, accompanied by energy accumulation, dissipation, and release. In other words, energy causes the failure of the samples, which leads to energy dissipation and release. The purpose of the study was to explore the law of energy evolution and the interrelations of various energy parameters of coal at different unloading levels. To achieve this purpose, the interrelations of the elastic and dissipated energy densities with the total input energy density and that between the dissipated and elastic energy densities in coal at different unloading levels were separately calculated by applying an area integral method. Different unloading levels were set for the four types of coal to further conduct a one-time loading and unloading test under uniaxial compression. On this basis, the following conclusions were drawn:

1. During a one-time loading and unloading test, the peak strength of coal in the failure process slowly decreased with the growth of the unloading level, which satisfied the relation of the linearly decreasing function. That is, the peak strength declined with an increasing unloading level. However, the reduction rates of the peak strengths of different coal samples with the unloading level were different, implying that different unloading levels showed diverse influences on the peak strengths of coal with different strengths.

2. The energy dissipation rate had nonlinear characteristics and could be affected by changes in its own characteristics, strength, and internal structure during loading and unloading. As the intensity increased, the shape of the dissipation rate fitting curve changed from an upper concave to a lower concave shape with the increasing strength, and the shape opening degree continued to increase. The nonlinear nature of the dissipation rate also reflected the integrity of the sample from the side. The greater the dissipation rate, the more defects the sample had, and the more complex the internal variation of the sample during loading and unloading.

3. The total input, elastic, and dissipated energy densities of the coal increased nonlinearly with the unloading level. This indicated that the energy evolution of coal showed a nonlinear characteristic and could be favorably fitted by using a quadratic function. According to the fitting curves, the growth rate of the total input energy density with the unloading level was the highest, followed by the elastic energy density, and the dissipated energy density exhibited the lowest growth rate with the unloading level. In the three groups of curves, the relationship curve between the elastic energy density and unloading level was highly consistent with the relationship curve between the total input energy density and unloading level.

4. The ratios of the elastic and dissipated energy densities to the total input energy density and the ratio of the dissipated energy density to the elastic energy density were all constants that satisfied the relation of the linear function. That is, the energy storage and dissipation grew linearly with an increasing unloading level.

5. As the strength increased, the input energy and the elastic energy density increased at a faster rate, and they observed the same law. There is an insignificant relationship between the degree of destruction of coal and the level of unloading. Energy is a major factor that drives the failure of the test piece, but it is not the main reason that determines the degree of damage to the test piece.

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NOMENCLATURE

List of symbols

| Symbol | Description |
|--------|-------------|
| \( U \) | Total input energy density (mJ mm\(^{-3}\)) |
| \( U^e \) | Elastic energy density (mJ mm\(^{-3}\)) |
| \( U^d \) | Dissipated energy density (mJ mm\(^{-3}\)) |
| \( \sigma \) | Stress (MPa) |
| \( \sigma_C \) | Uniaxial compressive strength (MPa) |
| \( \varepsilon \) | Strain |
| \( E \) | Elastic modulus (MPa) |
| \( E_L \) | Loading elastic modulus (MPa) |
| \( E_U \) | Unloading elastic modulus (MPa) |
| \( \alpha \) | Coefficient of energy storage |
| \( \beta \) | Ratio of dissipated energy density to elastic energy density |
| \( \eta \) | Dissipation rate |
| \( \gamma \) | Real unloading levels |
| \( \eta_A \) | Energy dissipation rate of Class A coal |
| \( \eta_B \) | Energy dissipation rate of Class B coal |
| \( \eta_C \) | Energy dissipation rate of Class C coal |
| \( \eta_D \) | Energy dissipation rate of Class D coal |
| \( \nu \) | Longitudinal wave velocity |
| \( \bar{\sigma} \) | Average wave speed |
| \( S \) | Standard deviation of wave velocity |
| \( S_c \) | Standard deviation of strength |
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