Experimental Investigation of Early-Warning Critical Energy for Strainbursts

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Received: 14 April 2021 / Accepted: 25 July 2021 / Published online: 13 September 2021
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Abstract This research aimed to establish an early-warning critical energy for coal instability based on the energy theory and acoustic emission characteristics of coal under triaxial compression. To obtain an early-warning critical strain energy indicating the increase in the risk of coal instability, conventional triaxial compression and acoustic emission (AE) tests were carried out on coal specimens taken from a 980-m-deep mine with initial confining pressures of 10, 15, 20, 25, 30 and 35 MPa. Stress–strain relations, AE features, and energy evolution characteristics during triaxial compression were analyzed. It was found that the energy evolution and AE event count changes across different loading stages. With increasing axial stress, most of the input energy stored in the coal specimens was in the form of elastic strain energy and the AE event count was close to zero, indicating that the coal grains reach a state of balance. After the elastic deformation stage, a portion of the input energy was consumed by inelastic deformation. Once the stress level exceeded the volumetric compressibility–dilatancy transition stress, the AE event entered a period of relative quiet, and the rate of energy dissipation abruptly accelerated, indicating that the coal grains achieved another state of balance before the instability or failure. The balance of the rock grains is broken again (AE event count and the rate of energy dissipation both increased dramatically), coal achieved the peak strength and instability soon. The point at which the dissipated energy ratio increased rapidly or the starting point of a quiet period, indicates an increase in the risk of coal instability. The corresponding elastic strain energy accumulated within the coal can be regarded as a precursor to instability or strainburst. Accordingly, a fitting formula is presented to predict the early-warning critical energy for brittle coal subject to different minimum principal stress. The analysis results in this paper can be helpful in the assessment of coal instability risk.

Keywords Acoustic emission · Elastic strain energy · Energy accumulation and dissipation · Coal instability
1 Introduction

Strainbursts in underground coalmines are one of the biggest hazards encountered during exploitation of deep coal seams (Luxbacher et al. 2008; Huang et al. 2018; Hebblewhite and Galvin 2017). Because strainburst often occurs in coal near or at the gateroad (which serves the longwall panels) boundary, these events not only endanger the lives of nearby workers, but also pose a very serious risk to equipment (Bukowska 2012; Mazaira and Konicek 2015; Zhao et al. 2017a; He et al. 2020). Hence, it is necessary to predict, as far as possible, the potential for a strainburst.

Numerous studies have been performed using different methods to evaluate the proneness of an intact rock mass to strainburst (Singh 1988; Adoko et al. 2013; Zhao et al. 2017b; Wang et al. 2017a). The stiffness method is often utilized based on the comparison of post-peak stiffness (or unloading stiffness) of the pillar in question with that of the host wall rock (Watson et al. 2014; Fakhimi et al. 2016; Ryder 1987; Maleki 2017). Many researchers also employ the stress method to better understand the mechanism of failure in hard, brittle rocks and their strainburst potential (Sharan 2007; He et al. 2010).

Since Cook first pointed out the link between excess strain energy and the damage due to strainbursts, an increasing number of studies have been performed using the energy method (Cook 1965a; Wang and Park 2001; Miao et al. 2016; He et al. 2016). Based on extensive theoretical investigations and experimental results from strainburst behavior studies, researchers have proposed different energy indicators, including the energy release rate (ERR) (Cook 1965b), the excess shear stress (ESS) (Kidybiński 1981), the elastic strain energy index ($W_e$) (Kwasniewski et al. 1994), and the burst potential index (BPI) (Mitri et al. 1999), etc., to evaluate strainburst potential. However, owing to the failure process that occurs in a strainburst and the complexity of the associated energy dissipation and release, these energy indicators are still limited (Yang et al. 2015; Qiu et al. 2014). Another shortcoming in the present understanding of strainbursts is the lack of reliable early-warning indicators to capture rock instability before strainburst occurs in cases of energy-driven instability. This shortcoming has prevented the establishment of an effective method for the predicting strainburst in rockburst-prone zones. Therefore, there is a need to establish a suitable criterion for the identification of coal capable of storing great levels of elastic strain energy.

Literature reviews have shown that uniaxial and triaxial compression tests are often used to investigate energy evolution associated with rock deformation and failure in the laboratory (Su et al. 2017; Sun et al. 2017), which can provide a description of strainburst behaviors from the perspective of energy. These conventional tests provide a unique boundary condition and stress path for rocks (e.g., rocks of the pillar skin or near the excavation boundary during excavation in deep civil tunnels) subject to uniaxial loading or triaxial unloading conditions. However, when considering a semi-infinite underground space subjected to initial far field stresses under plane-strain conditions, the surrounding rock of the gateroad areas (serving the longwall panels) is subject to a two-dimensional stress state, indicating that the radial or minimum principal stress $\sigma_3$ can be regarded as constant, and the tangential stress or maximum principal stress $\sigma_1$ increases (Wang et al. 2015; Jiang et al. 2016). Therefore, to investigate the strainburst process in the laboratory, the testing machine used should hold the value of $\sigma_3$ constant while increasing the $\sigma_1$ stress in the coal specimen. It is well known that conventional triaxial compression tests are capable of replicating this stress path.

The purpose of this paper is to establish an early-warning critical strain energy level that indicates elevated strainburst risk. The authors carried out conventional triaxial compression and acoustic-emission experiments. The experimental methods were developed to study stress–strain relations, the acoustic emission (AE) characteristics, and the energy evolution characteristics of coal samples during triaxial compression. Subsequently, based on the relationship between the pre-peak energy evolution law and the AE features, early-warning critical strain energy was obtained, and a formula is presented for determining the early-warning critical strain energy.
2 Deformation Behavior and Acoustic Emissions of Brittle Coal Under Conventional Triaxial Compression

2.1 Sample Descriptions

The studied coal specimens were extracted from a 980-m-deep coal roadway in the Xinhe coalmine (in the exploitation of coal seams in this mine, strainburst events were often encountered) in Jining City, Shandong Province, in northern China. The bulk density of the coal specimens varied in a small range from 1.56 to 1.65 g/cm³. The representative porosity of the specimens was 18.6%.

2.2 Testing Equipment

As shown in Fig. 1, the experimental system mainly consisted of a loading subsystem, an acoustic emission monitoring subsystem, and the load and displacement recording subsystem. AE activity was recorded by a CTA-2 acoustic emission data-acquisition system (made by the American Physical Acoustics Corp.), using two AE sensors with a frequency of 500 kHz. The amplitude threshold value of the sensors was set as 46 dB.

2.3 Experimental Setup

Conventional compression tests were carried out on the six samples with different confining pressures of 10, 15, 20, 25, 30, 35 MPa. The tests were conducted in the following two steps (Fig. 2): (1) the desired confining pressure was gradually applied at a constant rate of 0.1 MPa/s (oa) according to the hydrostatic pressure conditions; (2) the confining pressure was maintained while the deviatoric load was applied at a displacement-controlled loading rate of 0.002 mm/s (ac → cb) until the specimen was destroyed. According to the results presented by Meng et al. (Meng et al. 2016), the energy density evolution does not vary with the loading rate. Therefore, the loading rate in the tests was set as 0.002 mm/s.

All triaxial experiments were carried out using cylindrical specimens 50 mm in diameter and 100 mm in length in accordance with the ISRM standard, cored from the same coal blocks to minimize sampling variations. The ends and the sides of the specimen were carefully flat as required by the ISRM standard.
2.4 Analysis of Deformation Behavior
and Acoustic Emissions

In this paper, we focus on the observed stress–strain relationships and AE events. Figure 3 shows the stress–strain curves and AE cumulative counts plotted against the strain in the coal specimens under different confining pressures. For simplicity, Fig. 4 illustrates the typical stress-axial strain curve, the stress-volumetric strain curve, the AE cumulative counts-strain curve, and the AE counts-strain at a 10 MPa confinement.

(1) As shown in Figs. 3a–f, in all cases during the conventional triaxial compression test, the stress initially increased linearly in relation to the strain, indicating that crack closure may have occurred under hydrostatic pressure, and the coal sample exhibited elastic deformation. Following this period of pseudolinearity, the curves bent downwards prior to failure due to the growth of cracks within the specimens. After this peak strength, the coal specimens began to break and their ability to resist axial loads dropped. Note that a certain residual strength was still observed that increased with increasing confining pressure. Hu et al. and Wang et al. (Hu et al. 2017; Wang et al. 2017b) have suggested that the rock material enters the plastic stage when the axial stress exceeds the volumetric compressibility–dilatancy transition stress. As shown in Fig. 4, a volumetric compressibility–dilatancy transition point is observed in the stress-volumetric strain curve for a specimen at a confinement of 10 MPa. Overall, the stress-stain curves can be divided into four phases: (I) the elastic deformation stage, (II) the plastic stage, (III) the post-peak softening stage, and (IV) the residual strength stage.

(2) Corresponding to the stress–strain curve, the AE characteristics change regularly with strain (in Fig. 3), and thus can be used to reflect the failure process of coal samples. It can be seen that the variation of AE characteristics was similar with each other during triaxial compression. To investigate the general behavior of the specimens in a specific case, the test at a confinement of 10 MPa was used as a study case for the analysis of the failure process of brittle coal as shown in Fig. 4. In the elastic deformation stage, particles within the sample were dislocated by the external force and did not generate many AE events. After elastic deformation, as the stress exceeded the volumetric compressibility–dilatancy transition stress, the incidence of AE events increased dramatically, and then a relatively quiet period occurred before the AE counts increased rapidly in the vicinity of the peak strength (indicating that more microcracking was taking place) until instability and failure.

3 Energy Evolution in Conventional Triaxial Compression

3.1 Determination of Strain Energy

After uniform hydrostatic stresses are established, the axial stress $\sigma_1$ keeps doing positive work on the specimen before the load peak. In addition, the confining pressure $\sigma_3$ does negative work as it resists the radial dilation of the coal specimen. In other words,
the total input energy of the coal specimen was accumulated through the axial deformation by axial compression, while some of the energy was expended by the radial dilation. Therefore, the total input energy $U$ can be expressed as:

$$U = U_1 + U_2$$  \hspace{1cm} (1)
where $U_1$ is the absorbed strain energy due to axial deformation by axial compression after uniform hydrostatic stresses are established, and $U_2$ is the strain energy expended in resisting the radial dilation.

The absorbed strain energy $U_1$ and expended strain energy $U_2$ can be determined by the integral of the corresponding stress–strain curves (Fig. 4).

$$
U_1 = \int_{\varepsilon_1}^{\varepsilon_1} \sigma_1 d \varepsilon_1, \quad U_2 = 2 \int_{\varepsilon_3}^{\varepsilon_3} \sigma_3 d \varepsilon_3
$$

where $\varepsilon_1$ and $\varepsilon_3$ are the axial and radial strains at any unloading stress level, respectively. As shown in the Fig. 5, Eq. (2) is obtained by calculating the area of each trapezoid beneath the curve.

Therefore, according to the definition of integral calculus, the equations for the related energies are:

$$
U_1 = \sum_{i=1}^{n} \frac{1}{2} (\sigma_1^i + \sigma_1^{i+1}) (\varepsilon_1^i + \varepsilon_1^{i+1})
$$

$$
U_2 = \sum_{i=1}^{n} \frac{1}{2} (\sigma_3^i + \sigma_3^{i+1}) (\varepsilon_3^i + \varepsilon_3^{i+1})
$$

During the deformation and failure process under conventional triaxial compression, the coal specimen was generally regarded as a close-loop system with the assumption that there was no thermal transmission between the coal specimen and the external environment. Therefore, the energy balance can be described as following expression:

$$
U = U_e + U_d
$$

where $U_e$ represents the elastic strain energy stored in the coal specimen and $U_d$ represents dissipated energy owing to inelastic deformation and the closure, growth, and propagation of cracks.

The elastic strain energy $U_e$ under conventional triaxial compression is given by the following formula:
\[ U_e = \frac{1}{2E_u} \left[ \sigma_1^2 + 2\sigma_3^2 - 2\mu_u (2\sigma_1\sigma_3 + \sigma_2^2) \right] \] (6)

where \( E_u \) and \( \mu_u \) are the unloading modulus of elasticity and the unloading Poisson’s ratio, respectively.

Note that coal is a unique type of rock material, often riddled with initial flaws, such as joints and cracks within a coal sample, that increase the damaged of the sample under a conventional triaxial compression test. In this case, a progressive degradation of the sample stiffness would be observed. Based on this observation, we performed conventional triaxial cyclic loading–unloading compression test on coal specimens under different confining pressures of 10, 15, 20, 25, 30 and 35 MPa, and the resulting stress–strain curves are plotted in Fig. 2. The unloading modulus of elasticity and the unloading Poisson’s ratio were calculated based on the method suggested by Huang et al. (Huang and Li 2014), and plotted against cycle number in Fig. 6. The results can be summarized as follows: (1) for all test results, under the same confining pressure, the unloading modulus of elasticity \( E_u \) assumed a negatively exponential form as the cycle number increased, and as such, the final value of \( E_u \) was about 76% smaller than the modulus of elasticity measured at the first loading stage (Fig. 6a); (2) for all test results, the unloading Poisson’s ratio first increased rapidly and then became constant with the final value of \( \mu_u \) being about 54.26–122.55% greater than the Poisson’s ratio measured at the first loading stage (Fig. 6b); (3) during the same cycle, while the unloading modulus of elasticity increased with initial the confining pressure, the unloading Poisson’s ratio decreased. The above observations regarding the unloading modulus of elasticity and unloading Poisson’s ratio were also found by Heap and Faulkner (2008). These observations were used to calculate of elastic strain energy \( U_e \).

The unloading modulus of elasticity \( E_u \) and the unloading Poisson’s ratio \( \mu_u \) depend on the extent of the sliding of pre-existing cracks and crack-like voids within the rock material. Walsh et al. (Walsh 1965) and Heap et al. (Kolupaeva et al. 2006), indicated that the stress-induced positive sliding or reverse sliding of crack faces introduced nonlinearity and hysteresis into the stress–strain curve of a specimen during unloading. This is in good agreement with the experimental results in the present study.

### 3.2 Energy Conversion Process at Pre-Peak Stage Under Conventional Triaxial Compression

Using the methods described in Sect. 3.1, the corresponding energy (eg. \( U, U_e \) and \( U_d \)) was calculated. Here, we mainly focus on the variation rules for total input energy \( U \), elastic strain energy \( U_e \), and dissipated energy \( U_d (U-U_e) \) in compression with the change in axial stress and confining pressure (Fig. 7). Observations can be generalized as follows:

Through comparison of all test results, the total input energy \( U \), the elastic strain energy \( U_e \), and the dissipated energy \( U_d \) were found to increase nonlinearly with axial stress and exhibit a similar nonlinear
Fig. 7  Calculation results of the total work done, elastic strain energy, and dissipated energies during conventional triaxial compression for confining pressures of (a) 10 MPa (b) 15 MPa (c) 20 MPa (d) 25 MPa (e) 30 MPa (f) 35 MPa
behavior in the pre-peak stage (Fig. 7). During the elastic deformation stage, the total input energy \( U \) and the elastic strain energy \( U_e \) both increase rapidly while the dissipated energy \( U_d \) remained at about zero. This indicates that at the elastic deformation stage, most of the input energy is converted into elastic strain energy and stored in the coal specimens. After the elastic deformation stage, the coal specimen enters the plastic stage and generates inelastic deformation. During this stage, the total input energy \( U \) increases rapidly, followed by the increase in elastic strain energy \( U_e \), and the dissipated energy \( U_d \) begins to increase rapidly as well. It can also be inferred that while a part of the input energy is dissipated by inelastic deformation, and the closure, growth and propagation of cracks, the rest of the input energy is still stored in the form of elastic strain energy (\( U_e \)). Taking the test at \( \sigma_3 = 10 \) MPa as an example (Fig. 7a), when the axial stress was about 40 MPa, \( U_e \) was about 111.28 kJ/m\(^3\), twelve times higher than the dissipated energy \( U_d \) (9.22 kJ/m\(^3\)). This means that although some energy was dissipated, in the plastic stage most of the input energy \( U \) was still accumulated in the form of elastic strain energy \( U_e \).

In addition, according to Fig. 7, the elastic strain energy \( U_e \) and dissipated energy \( U_d \) both increase nonlinearly with axial stress under different confining pressures and maximize at the end of the plastic stage, which is similar to an “S-curve.” To model the growth of \( U_e \) and \( U_d \), we used the Pearl Model S-curve (Kolupaeva et al. 2006). The Pearl model curve is determined by three coefficients, \( a \), \( b \), and \( c \) as a function of least squares regression (see Eq. 7), with values listed in Table 1. The coefficients of determination range from 0.96327 to 0.9941 indicating that the proposed formula produces accurate results.

\[
U_i = a \left(1 + e^{-b \bar{r}^c}\right)
\]  

where \( U_i \) is the elastic strain energy \( U_e \), or the dissipated energy \( U_d \). \( \sigma_p \) is the peak strength, and \( \sigma \) is the axial stress. Variables \( a \), \( b \), and \( c \) are the Pearl model constants which can be obtained from test results. The resulting \( R^2 \) values suggest that Eq. (7) can be used to estimate \( U_e \) and \( U_d \) accurately when the peak strength and axial stress are known.

Figure 8 illustrates the influence of the confining pressure on peak total input energy \( U \), the elastic strain energy \( U_e \), and the dissipated energy \( U_d \). In the figure, the peak values of \( U \), \( U_e \), and \( U_d \) indicate the corresponding parameters for different confining pressures at peak strength. It can be seen that the peak values of \( U \), \( U_e \), and \( U_d \) of the coal specimens increased linearly with increasing confining pressure. For \( \sigma_3 = 10 \) MPa, the peak values for \( U \), \( U_e \), and \( U_d \) were 323.35, 249.24 and 74.12 kJ/m\(^3\), respectively. However, when \( \sigma_3 \) was increased to 35 MPa, the peak values of \( U \), \( U_e \), and \( U_d \) increased to 1537.02, 965.38, and 571.64 kJ/m\(^3\), respectively. This indicates that the higher the initial confining pressure, the greater the peak values of \( U \), \( U_e \), and \( U_d \). Under the highest initial confining pressures, coal strength is enhanced and leads to greater energy accumulation and dissipation. This observation may explain why high-stress induced strainbursts often release high elastic strain energy.

### 3.3 Energy Conversion Rate at Pre-Peak Stage

To describe the energy conversion rate under conventional triaxial compression, the elastic strain energy ratio \( \beta \) and the dissipated energy ratio \( \alpha \) were investigated. The elastic strain energy ratio and the dissipated energy ratio are respectively defined as the

| \( \sigma_3/MPa \) | \( U_e \) | \( U_d \) |
|-----------------|-----------------|-----------------|
|  | \( a \) | \( b \) | \( c \) | \( R^2 \) | \( a \) | \( b \) | \( c \) | \( R^2 \) |
| 10   | 5.41682 | 3.47462 | \( - \) | 0.415 | 0.98956 | 0.19464 | 8.69069 | 2.69282 | 0.9941 |
| 15   | 5.92628 | 3.33643 | \( - \) | 0.90041 | 0.98173 | 0.28764 | 8.46119 | 2.4154 | 0.98834 |
| 20   | 6.14103 | 3.44282 | \( - \) | 1.33177 | 0.98625 | 0.37958 | 7.90145 | 1.22108 | 0.99367 |
| 25   | 10.40432 | 3.10994 | \( - \) | 1.25655 | 0.97894 | 0.6229 | 7.31862 | 1.17037 | 0.99427 |
| 30   | 7.22087 | 3.22081 | \( - \) | 1.68414 | 0.98973 | 0.29416 | 9.0878 | 1.79151 | 0.99306 |
| 35   | 11.5649 | 3.11441 | \( - \) | 1.35613 | 0.99202 | 0.1129 | 14.49295 | 5.91933 | 0.96327 |
ratio of elastic strain energy or dissipated energy to the total work done (Eq. 7).

\[ \beta = \frac{U_e}{U} ; \quad \alpha = \frac{U_d}{U} \]  

(7)

In Fig. 9, under the same confining pressure, the pre-peak elastic strain energy ratio \( \beta \) and dissipated energy ratio \( \alpha \) exhibit nonlinear hysteretic behavior with the change in axial stress. In general, the pre-peak elastic strain energy ratio \( \beta \) is always larger than the dissipated energy ratio \( \alpha \). Therefore, during the process of deformation and failure, with the constant work done by the testing machines, most of the total input energy is converted to elastic strain energy \( U_e \). The rest of the total input energy is consumed by the plastic deformation and crack initiation and propagation (associated with \( U_d \)).

Taking the test at \( \sigma_3 = 10 \) MPa as an example (Fig. 9a), the analysis indicates the following: (1) within \( \sim 0\% - 86.23\% \) of the peak strength \( \sigma_p \) (in the elastic deformation stage), the elastic strain energy ratio \( \beta \) is nineteen times that of \( \alpha \). It can be deduced that the input energy \( U \) is almost equal to the elastic strain energy \( U_e \), indicating that the cracks do not propagate (this can also be seen in the values of AE count and energy, which are smaller); (2) interestingly, when the axial stress increases from 86.23\% to 100\% of the peak strength (in the plastic stage), the pre-peak dissipated energy ratio \( \alpha \) sharply increases from a stable region to a nonlinear region. As the elastic strain energy is released in the form of the surface energy of cracks, the value of \( \beta \) decreased rapidly. In contrast, \( \alpha \) increased rapidly, indicating that damage may be pronounced and the cracking process accelerates abruptly prior to failure.

4 Determination of Early-Warning Critical Energy for Strainbursts

Based on the in-situ and experimental investigations, (Feng et al. 2012) and (Nemat-Nasser and Horii 1982) found that the evolution process of a strainburst was often accompanied with the cracking of brittle rock material. Identification of early-warning key points for strainbursts did not indicate that coal/rock instability was immediately obvious, but that the rock had entered a stage of crack propagation. In this study, we analyzed one case of confining pressure as an example (\( \sigma_3 = 10 \) MPa) to determine the early-warning critical energy for strainbursts (Fig. 10).

As discussed above, the dissipated energy ratio \( \alpha \) and the AE event characteristics provide a description of crack initiation, growth, and propagation. According to the recorded AE events, when the stress...
Fig. 9 Variation of the energy ratios $\alpha$ and $\beta$ in the pre-peak stage during conventional triaxial compression for confining pressures of

(a) 10 MPa
(b) 15 MPa
(c) 20 MPa
(d) 25 MPa
(e) 30 MPa
(f) 35 MPa
exceeded the volumetric compressibility–dilatancy transition stress (yield point), there was a relatively quiet period of AE events before coal failure, which may describe the state of coal change. This change can be explained from the perspective of energy: when the coal is loaded in the elastic deformation stage ($\sim 0\text{–}86.23\%$ of the peak strength $\sigma_p$), only elastic deformation is generated and the dissipated energy (responsible for plastic deformation and crack propagation) is about zero. Here, the coal grains reach a state of balance. When the stress approaches the yield point, numerous new cracks are generated. They are then propagated into macrocracks and driven by the dissipated energy, which causes a large number of high-energy AE events, as well as volumetric dilatancy. As the balanced state is upset by this cracking, the accumulated elastic energy is released in the form of surface energy of cracks, and the dissipated energy ratio $\alpha$ increases rapidly. Under the constant load, the coal grains achieved another state of balance indicated by the occurrence of an AE event quiet period. During this quiet period, the dissipated-energy-driven extension and connection of microcracks constantly occurs, and the volumetric strain continues to increase. As more macrocracks are generated, the balance of the rock grains is broken again, which causes a large number of high-energy AE events. At this point, the coal approaches peak strength and instability. Therefore, an observed decrease in these AE events, which indicate namely a rapid increase in the dissipated energy ratio $\alpha$, can be used as the “precursor to failure” marker. This precursor to failure does not directly represent coal instability, but instead that the coal has entered the stage of crack propagation. In this study, the precursor point for the failure and instability of coal was set at the beginning of quiet period. Therefore, the corresponding early-warning critical energy at the “precursor point” can be obtained by using Eq. (7).

Based on the presented analysis, we can determine a precursor point and corresponding early-warning critical energy under the other confining pressures of 15, 20, 25, 30 and 35 MPa. The precursor point and corresponding early-warning critical energy are illustrated in Fig. 11.

It can be observed that stress at the precursor point, when normalized to the peak axial stress, is 0.859, indicating that the value of precursor stress is independent of confining pressure. Considering that the deviation of some points might be somewhat large, more tests on additional coal specimens should be conducted to verify the correct stress level for the precursor stress. Nevertheless, the determined stress level may be considered to represent a characteristic of internal microcrack propagation in the coal prior to failure, an approach validated by the volumetric compressibility–dilatancy transition. When the load reaches this stress level, the initiation and propagation

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**Fig. 10** Variation of recorded AE event counts and the dissipated energy ratio at pre-peak stage ($\sigma_3 = 10$ MPa)
of microcracks is abruptly accelerated, which ultimately results in the failure of the coal.

Entering the obtained precursor stress into Eq. (7), the early-warning critical energy can be calculated. The relationship between the early-warning critical energy and the confining pressure is shown in Fig. 11, in which it can be seen that the early-warning critical energy is positively related to confining pressure. Using an exponential regression function, the early-warning critical energy can be approximated by the following formula Eq. (8).

\[ U'_e = 16.7871\sigma_3^{1.0546} \quad R^2 = 0.98001 \]  

Where \( U'_e \) is the early-warning critical energy for strainbursts and \( \sigma_3 \) is the confining pressure. A square regression coefficient of \( R^2 = 0.98001 \) is obtained, suggesting that Eq. (8) can be used to estimate early-warning critical energy when the confining pressure is known. Note that the formula in Eq. 8 is suitable for confining pressures of 10 MPa \( \leq \sigma_3 \leq 35 \) MPa.

5 Discussion

Strainbursts in deep coal seam mining have been a well-known problem for a long time (Luxbacher et al. 2008; HuangW et al. 2018). These events can cause severe damage to facilities, equipment and may result in fatalities (Hebblewhite and Galvin 2017; Bukowska 2012; Mazaira and Konicek 2015). The forecasting of strainbursts in deep coal seam mining is the foundation for protection against and prevention of such damage. This research aimed to establish an early-warning critical energy for strainbursts based on the energy theory and acoustic emission characteristics of coal under triaxial compression.

The changes in AE activity and dissipated energy are inevitably associated with the development and evolution of cracking within the coal (Meng et al. 2016; Huang and Li 2014; Peng et al. 2015). After testing at different confining pressures, the pre-peak stress–strain curves of coal exhibited the following stages: an elastic deformation stage, and a plastic stage. As illustrated in Fig. 2 and Fig. 9, the dissipated energy ratio \( \alpha \) and the AE event count changes between different loading stages. The stability and durability of the rock increased, indicating that damage accumulation was gentle and the coal state has relative stability. Along with the observed deformation of the coal, when the stress approached the volumetric compressibility–dilatancy transition point, the AE events increased dramatically, and then entered a relatively quiet period at which time the dissipated energy ratio \( \alpha \) exhibited a sharp increase, indicating the cracking process had abruptly accelerated prior to the occurrence of coal instability or failure. Therefore, it is possible to determine the state...
of rock instability by tracking the changes in the dissipated energy ratio $a$ and AE event count.

From the perspective of energy, coal damage or failure could be regarded as an energy-driven instability (Singh 1988; Wang et al. 2017a; Meng et al. 2016). As shown in Fig. 7 and Fig. 10, the dissipated energy leads to inelastic deformation and crack development, etc. and weakens the ability of the coal to resist failure. The accumulated elastic strain energy in the coal is the main driving energy source for the coal instability or failure, e.g. higher accumulated elastic strain energy leads to greater energy releases. The energy storage limitation represents the maximum ability to support applied load (e.g. the coal peak strength). Once the accumulated elastic strain energy reaches the energy storage limitation, coal failure or instability occurs accompanied by a large energy release. The early-warning critical energy, representing the stored energy (at which time coal failure/instability is immediately obvious), is the point indicating that the coal has entered the abrupt cracking stage, and accordingly, there is an increased risk of rock rupture and instability. Furthermore, from Fig. 11, the early-warning critical energy was found to increase with higher confining pressures. When $\sigma_3 = 10$ MPa, $U_0^e$ was 169.34 kJ/m$^3$, whereas when $\sigma_3$ was increased to 35 MPa, $U_0^e$ increased to 690.02 kJ/m$^3$. This indicates that the proneness of an intact rock mass to coal instability was restrained by high minimum principal stress $\sigma_3$. This is in good agreement with the stress criterion established by He et al. (2010).

The early-warning critical energy detailed in this paper describes the stage of internal microcrack propagation prior to failure and can be easily determined. In conjunction with numerical analysis (i.e., FEM or DEM models) of the extent of strain energy distribution and accumulation induced by mining operations, the zones in the mined coal seam with a high risk for coal instability could be mapped to indicate where appropriate protective measures should be taken. However, it should be mentioned that coal is a unique type of rock material, and as such, it often contains initial flaws (e.g. pores and cracks) that could have a significant effect on the deformation and AE characteristics of the rock. Therefore, additional tests on other coal specimens, or even other materials, should be conducted to verify the proposed method.

6 Conclusions

The aim of this study was to lay a foundation for coal instability danger assessment by describing the energy evolution in coal under conventional triaxial compression. The results of the tests presented in this paper can be summarized in follows:

1. During the triaxial compression process, the acoustic emission response can reflect the fracture evolution of coal. In the initial elastic deformation stage, low magnitude and low energy AE events were generated. When the stress exceeded the volumetric compressibility–dilatancy transition stress, a relatively quiet AE period occurs immediately prior to coal failure or instability.

2. Coal failure or instability is energy-driven. The energy evolution of confined brittle coal is closed when related to the axial loading stress, rather than to the confining pressure. The proposed Eq. (7) can describe the change of energy density in coal specimens.

3. The dissipated energy ratio $a$ increases rapidly accompanying the occurrence of a quiet period of AE events prior to instability. The point at which the AE events decrease, indicating a rapid increase in the dissipated energy ratio $a$, is identified as the “precursor to failure.” The occurrence of this precursor indicates that the coal has undergone early damage and the risk of confined brittle coal instability has increased, providing an early-warning critical energy for coal instability. A fitting formula is presented to predict the early-warning critical energy for brittle coal subject to minimum principal stress.

Acknowledgements The research described in this paper was financially supported by Engineering Laboratory of Deep Mine Rockburst Disaster Assessment Open Project (LMYK2020009).

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