Research Article

Numerical Study on Coal Burst Proneness Characteristics of Fissured Coal Mass

Zhijie Zhu, Zhenhua Yao, Jan Nemcik, Laigui Wang, Jun Han, and Lihai Tan

1School of Mining, Liaoning Technical University, Fuxin, China
2State Key Laboratory of Coal Mining and Clean Utilization, Beijing, China
3School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia

Correspondence should be addressed to Zhijie Zhu; zhuzhijie@lntu.edu.cn

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1. Introduction

Coal burst is defined as the violent and sudden failure of coal mass, causing the instantaneous release of accumulated elastic energy [1]. It leads to a high-velocity expulsion of the broken coal pieces into the working space and destroys equipment and facilities [2–11]. As the coal mining depth increases, this hazard poses a challenge to a large number of coal mines all over the world. For example, a coal burst occurred on 15 April 2014 at the Austar Coal Mine in Australia, causing two miner fatalities in the longwall development gate road and damage to the mining equipment [12]. In the USA, a coal burst occurred caused by an extensive pillar failure at the Crandall Canyon coal mine in 2007, and six miners and three rescue workers were killed [13]. In China, a coal burst occurred at the Sunjiawan coal mine in 2005, and 214 miners were killed [14]. In fact, there are often a large number of structurally weak planes such as bedding, joints and fissures in coal and rock masses. The instability and failure of coal masses are influenced by the morphological characteristics of the structural planes (angle, scale, shape, etc.). The study of the coal burst proneness of the structural plane is more in line with the actual situation, and can more truly reflect the failure and instability process of the coal mass.

Burst proneness is an inherent mechanical property of coal/rock mass, which can be used to indicate the ability of the coal mass to accumulate energy that would eventually lead to a dynamic failure [15]. Hence, it can reflect the risk of coal burst to some extent. Many scholars have proposed various burst proneness indexes. Szecowka et al. [16] proposed the strain energy storage index \( W_{ES} \), which is the ratio of elastic energy to plastic energy during a single loading-unloading cyclic uniaxial compression test. The bursting energy index \( K_E \) was defined by Gil and Drzezla [17] as the ratio of the kinetic energy of coal fragments to the maximum accumulated strain energy under uniaxial compression. The rheologic ratio was presented by Kidybinski [18], which can
be calculated as the ratio of the dynamic resistance stress rate to the average stress relaxation rate. The burst energy release index was introduced by Singh [19], which is a measure of the energy released at the time of rock fracture. Kwasniewski et al. [20] claimed that the elastic strain energy is a significant contributing factor in bursting, and that it can be calculated by the uniaxial compression strength and the unloading tangential modulus. Wu and Zhang [21] suggested that coal specimen failure duration (Dt) in uniaxial compression test can be used to determine the bursting proneness. The burst potential index was established by Mitri et al. [22], showing that the closer the stored energy was to the limited energy storage, the greater the possibility of rock burst was. Wiles [23] successfully used the local energy release rate (LERR) to predict pillar burst, and it can be calculated by dividing the total released energy by total volume. To reflect the relationship between energy storage and energy dissipation in bursting, Tang et al. [24] proposed the surplus energy index based on the energy variation in the deformation processes. Guo and Su [25] introduced the effective burst energy index, which is the ratio of the elastic energy stored in the coal specimen before the peak strength to the energy released during the post-peak stage in the compression test. Residual energy emission speed was defined by Zhang et al. [26] as the residual energy release per unit time during coal destruction. Qi et al. [27] put forward the uniaxial compressive strength as a new index to evaluate coal burst proneness. Gong et al. [28] established the peak-strength strain energy storage index for rock burst proneness, which is the ratio of elastic strain energy density to dissipated strain energy density when loading to the peak compressive strength.

It can be seen that great progress has been made in research on burst proneness. However, there are few studies on the effect of structural planes on coal burst proneness. The existing research results show that the elastic modulus, peak strength, and prepeak energy accumulation of coal are all related to structural planes. Since the coal burst proneness is closely related to the prepeak accumulated energy and post-peak released energy, the coal burst proneness should also be deeply influenced by structural planes. Recently, Feng and Zhao [29] argued that the burst proneness was significantly affected by the heterogeneous characteristics of the specimen. Li, Jiang [30] postulated that the value of the pore compressibility coefficient of specimens with high bursting proneness was larger than that of medium bursting proneness. Li et al. and Lu et al. [31, 32] considered that structural weak planes such as bedding (penetrating fissure) induced anisotropic characteristics of the coal burst proneness. However, little work has been done on the nonpenetrating fissured coal/rock mass. The crack propagation penetration, failure mode, and fracture mechanism of coal mass with nonpenetrating fissures under the action of mining disturbance are substantially different from those of coal with penetrating fissures. Therefore, it is necessary to study the coal burst proneness characteristics of coal with nonpenetrating fissures.

In this study, two evaluation indexes of coal burst proneness were used based on energy transformed analysis of fissured coal specimens. The calibrated PFC2D model of coal specimens with various fissure configurations (single fissure, two non-coplanar-parallel fissures and two coplanar-parallel fissures) was established and uniaxial compression tests were conducted to analyze the coal burst proneness of fissured coal mass. The relationships between coal burst proneness and crack initiation stress, crack initiation stress level, and elastic strain energy distribution were analyzed, and the results can be used as a guideline for forecasting and preventing coal burst.

2. Energy Conversion Analysis of Fissured Coal under Uniaxial Compression Test

The existence of fissures changes the crack propagation mode and mechanical properties of the specimen, weakens its integrity to a certain extent, and reduces the ability of stored energy. Therefore, the energy evolution process of the fissure specimen is obviously different from that of the non-fissure specimen. Under the action of external force, the opening, closing, expansion and penetration of the internal cracks in the coal mass generate new shear sliding surfaces, and finally form macroscopic cracks, resulting in instability and failure of the coal mass. The propagation process of fissured coal mass is accompanied by the transfer and release of energy, which has an important influence on the coal burst proneness. Figure 1 shows the stress–strain curve of a fissured coal specimen under uniaxial compression [33, 34]. The deformation process followed five stages corresponding to different energy transformation:

1. Fissure closure stage (OA). The preexisting fissures in the coal are gradually compacted. The external energy input by the testing machine onto the specimen is converted into elastic potential energy and is stored in the coal mass.

2. Linear elastic stage (AB). Once the fissures in the coal mass are completely closed, the sample enters the linear elastic deformation stage (AB). $\sigma_{c}$ is the crack closure stress. At this stage, the energy input by the testing machine is converted into elastic potential energy.

3. Stable crack growth stage (BC). As the axial stress at both ends of the coal specimen gradually increases to the crack initiation stress $\sigma_{c}$, new cracks begin to appear, and the stress–strain curve enters the stable crack propagation stage. The crack initiation stress $\sigma_{c}$ is 30%-50% of the peak strength. The number of internal microcracks gradually increases and pre-existing fissures begin to expand. At this stage, the energy input by the testing machine is converted into elastic potential energy, microcrack surface energy and plastic potential energy. In this process, there is also a release of heat energy, electromagnetic radiation, and acoustic emission energy. The elastic energy still dominates, as opposed to other energy forms.

4. Accelerated crack growth stage (CD). When the axial stress gradually increases to the crack damage stress...
σ_{cd}, the stress–strain curve enters the accelerated crack growth stage. The crack damage stress is 70%-80% of the peak strength. The coal specimen obviously yields, but it remains intact. At this stage, the number of microcracks increases rapidly, and the preexisting fissures continuously expand. Dissipated energy such as radiant energy and surface energy increases significantly, and the storage rate of elastic strain energy gradually slows down.

(5) Post-peak accelerated rupture stage (after point D).

As the axial stress continues to increase, the microcracks in the coal specimen penetrate each other and form a macroscopic tension fracture zone or shear zone, and the rock sample suffers macroscopic damage. At this time, the corresponding axial stress is the peak strength σ_{p}, and the internal elastic strain energy reaches the highest value. In the post-peak stage, a large number of microcracks are generated inside the specimen. The microcracks eventually converge into macroscopic cracks, leading to the complete destruction of the specimen. At this stage, the previously stored elastic potential energy is released and transforms into crack surface energy, plastic potential energy, kinetic energy, and radiant energy. The surface energy, plastic potential energy and kinetic energy are more significant than other energy forms.

Currently, the dynamic failure duration, the strain energy storage index (W_E), the bursting energy index (K_E) and the uniaxial compressive strength are the most commonly used indicators of coal burst proneness. The advantages and disadvantages of the four coal burst proneness indicators are discussed as follows:

(1) The dynamic failure duration is the time from the peak strength to the complete loss of bearing capacity of the specimen under uniaxial compression. This evaluation index has certain limitations: ① there is a certain residual strength after the specimen is damaged, and the determination of the residual strength directly affects the final value of the dynamic failure duration. At present, the determination of the residual strength has not been clearly defined. ② The remaining energy of coal specimen failure is not explained. If the dynamic failure duration is short and the remaining energy converted into kinetic energy is small, the burst proneness is not necessarily high.

Figure 1: Stress–strain curve of a fissured coal specimen under the uniaxial compression test [35].
(2) The bursting energy index ($K_E$) closely links the accumulation and consumption of deformation energy, and better reflects the energy conversion relationship in the coal mass during the occurrence of coal burst, which is of great significance for revealing the mechanism of coal burst. Since the envelope area of the stress–strain curve at the front of the peak contains a part of the energy dissipated due to irreversible plastic deformation, the coal burst proneness is higher than the actual value.

(3) The strain energy storage index ($W_{EE}$) reflects the ratio of the accumulated elastic energy to the plastic deformation energy before the peak strength, but the ratio cannot reflect the accumulated elastic energy. Suppose there are two groups of coal specimens, in which the elastic strain energy and the plastic strain energy of the first group are 10 and 2, respectively, and its elastic strain energy index $W_{EE}$ is equal to 5, while the elastic strain energy and plastic strain energy of the second group are 5 and 1, respectively, and its elastic strain energy index $W_{EE}$ is also equal to 5. In this case, the coal burst proneness should be the same. However, due to the difference in the accumulated elastic energy of the two groups, the residual energy is also different, and so the coal burst proneness is different. Therefore, the elastic strain energy index ($W_{EE}$) cannot accurately reflect coal burst proneness.

(4) The uniaxial compressive strength has a certain correlation with other coal burst proneness indices [27], but it cannot directly reflect its energy accumulation and release capacity during the loading process.

The existing coal burst proneness indices can reflect the elastic energy accumulation before the peak of the specimen or the energy consumption after the failure to a certain extent, or the relative relationship between the two. Therefore, the energy index is more comprehensive and better reflects the coal burst occurrence mechanism. In the process of coal damage under load, when the released energy is greater than the consumed energy, the remaining energy is converted into debris ejection kinetic energy, resulting in coal burst. The energy difference between the elastic energy accumulated before the peak and the energy consumed after the peak is the effective energy source for the coal burst. Additionally, the accumulation of elastic energy at peak strength can reflect the ability of the coal mass to store energy. Therefore, the elastic strain energy (ESE) [20] and residual energy index (REI) [36] chosen in this paper can avoid the above problems, and the index calculation process are as follows:

The accumulated energy in uniaxial compression is shown in Figure 2(a). Apart from the elastic strain energy, the dissipated energy also contributes a small portion to the total input energy during the loading process. When the specimen is unloaded at peak strength, elastic deformation recovers. So, the area under the unloading curve in Figure 2(a) is the accumulated elastic strain energy $E_{1}$. The area between the loading curve and the unloading curve is the dissipated energy $E_{1}$, including plastic strain energy and crack surface energy and so on. During the post-peak stage, new microcracks penetrate and converge to form macrocrack cracks, causing specimen destruction with a large amount of elastic strain energy released. A small portion of the released energy $E_{3}$ is used for the elastic recovery of the test machine, while most of the energy is used for macroscopic crack slip and propagation. When the elastic energy $E_{3}$ is greater than the released energy $E_{3}$, the remaining energy is be released in other forms such as kinetic energy, vibration and sometimes sound, along with coal burst. The severity of the coal burst depends on the amount of remaining energy, which is closely related to the elastic strain energy $E_{3}$ and the released energy $E_{3}$. The elastic strain energy $E_{3}$ can reflect the ability of storing energy of the coal mass, which provides an energy source for the coal burst. Therefore, in this paper, the elastic strain energy $E_{2}$ (ESE) and residual energy index (REI) are chosen as evaluation indexes of coal burst proneness. The residual energy index (REI) can be defined according to:

$$REI = \frac{(E_{2} - E_{3})}{E_{3}}$$

It is difficult to perform an unloading test at the peak strength point. The elastic strain energy $E_{2}$ at the peak strength

**Figure 2**: Sketch of energy accumulation of coal specimen [38]: (a) unloading at peak strength and (b) unloading at 80% of peak strength.
was estimated according to the stress–strain characteristics before the peak strength [37]. The ratio of elastic strain energy $E_1$ to the total input energy ($E_2 + E_3$) is the same for the two situations and hence, the residual energy index (REI) can be evaluated by loading to about 80% of the peak strength and unloading to 0 and re-loading to complete destruction (Figure 2(b)). Sometimes, the two resultant indicators might be contrary to each other, and in this case the residual energy (RE) value can be used for coal burst proneness evaluation. The residual energy (RE) can be calculated by REI and ESE according to:

$$RE = E_2 - E_3$$

(2)

3. Numerical Modeling

3.1. Numerical Modeling Methods. At present, numerical simulation methods mainly include continuum methods and discontinuous medium methods. Traditional continuum methods (such as finite element) have certain limitations in dealing with crack initiation and extension due to problems such as mesh re-division and crack tip singularity. Discontinuous media methods (such as particle flow discrete elements) idealize the system as a series of discrete elements, and directly express the damage as the failure of the contact between the elements, without making assumptions about crack propagation. The problem of crack extension, in which the particle flow software PFC is widely used.

In PFC2D, material can be simulated by the assembly of variably sized rigid particles. Interaction between particles is through the microbond model. Contact bond (CB) and parallel bond (PB) model are two types of microbond models, as shown in Figure 3 [39]. The CB can only transfer forces between particles, while the PB can transfer both moments and forces. A parallel bond (PB) can be considered as elastic springs with constant shear and normal stiffness, uniformly distributed over a cross-section lying on the contact plane and centered at the contact point [40]. Moreover, PB breakage in either shearing or tension can cause an immediate reduction in macro stiffness [41]. Therefore, the PB model is more realistic for rock/coal mass studies [42]. The smooth joint contact model is used for simulating fissures.

3.2. Modeling Parameters and Calibration. The microparameters in PFC2D were difficult to determine. In order to validate the particle properties, the correlation between the macrobehavior and the microparameters was essential to establish. The “trial and error” method was used in this calibration process [43]. The macroscopic mechanical properties of intact coal specimens were obtained through the uniaxial compression test. The microparameters of coal specimen in the PFC2D model (as shown in Table 1) were determined by back analysis of the laboratory test results.

The stress–strain curves resulting from the uniaxial compression test in numerical modelling and laboratory experiment are compared in Figure 3. The size of the experimental specimen was 50 mm × 50 mm × 100 mm, the YAW2000C rock mechanics test system was used for loading, and the loading rate was 0.01 μm/s. The simulation results agreed well with the experiment results. However, the experimental specimen exhibited nonlinear deformation at the beginning of loading, which was caused by the closure of initial pores and fissures in coal specimen. By contrast, this nonlinear deformation did not occur in the numerical model. Table 2 lists comparisons of macromechanical parameters between numerical model and experimental test. The uniaxial compressive strength (UCS), Young’s modulus and Poisson Ratio obtained from the numerical modeling were close to those determined by laboratory experiment.

The smooth joint model was used to simulate fissures mechanical behavior. The normal stiffness, shear stiffness
and coefficient of friction were set at 200 GPa/m, 50 GPa/m and 0.78, respectively [44].

3.3. PFC<sup>2D</sup> Model and Simulated Schemes. The dimensions of the coal specimen in the numerical simulation were 100 mm in height and 50 mm in width. The PB model and smooth joint model were used to simulate microbonds between particles and fissures, respectively. In the uniaxial compression test, the loading rate was set at 0.01 μm/s. In order to calculate coal burst proneness, the simulation was conducted in two stages. In the first stage, the specimen was loaded to complete destruction, and uniaxial compressive strength was determined. In the second stage, the specimen was loaded to 80% of the uniaxial compressive strength and unloaded to zero. The total input energy was calculated based on the stress–strain curve in the first stage. The ratio of elastic strain energy to the total input energy was calculated in the second stage. As a result, the elastic strain energy (ESE) was calculated by the total input energy in the first stage multiplying the ratio of elastic strain energy to the total input energy. Hence, the residual energy index (REI) was calculated according to equation (1).

There are fissures in the actual coal mass, and the layout of the fissures has a significant impact on the distribution of the surrounding stress field and the damage model. Therefore, it is of great significance to study the mechanical behavior of typical fissure configurations to determine the coal burst proneness and coal burst mechanisms of fissured coal mass. The distribution of fissures in coal and rock mass under actual conditions is quite different, and it is difficult to reflect the mechanical properties of the actual cracks distribution from experimental view. In this paper, the actual fissures are simplified into three modes: single fissure, two non-coplanar-parallel fissure and two coplanar-parallel fissure. The energy evolution and coal burst characteristics under these three conditions could provide theories base for the study of coal burst under actual fissured coal mass. To investigate the mechanical behavior of fissured coal mass, different fissure types such as single fissure, two non-coplanar-parallel fissures and two coplanar-parallel fissures were simulated. The parameters of various fissure configurations were as follows:

1. For single fissure coal specimens: fissure length \( l = 20 \) mm, fissure inclination angle \( \beta = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, \) and \( 90^\circ \)

2. For two non-coplanar-parallel fissure coal specimens: fissure \( l = 20 \) mm, fissure’s distance \( s = 10 \) mm, fissure inclination angle \( \beta = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, \) and \( 90^\circ \). The length of the fissure was 20 mm, which is the same as the length of a single fissure, in order to analyze the influence of the number of fissures on the coal burst proneness

3. For two coplanar-parallel fissure coal specimens: fissure length \( l = 10 \) mm, fissure’s distance \( s = 10 \) mm, fissure inclination angle \( \beta = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, \) and \( 90^\circ \). The length of the fissure was 10 mm, which is the same as the total length of a single fissure, in order to analyze the influence of the fracture discontinuity on the coal burst proneness

Numerical specimens of various angled fissures should be calibrated by experimental results before simulation. After an extensive literature search, it was found that there are few studies on the coal burst proneness and failure mode of fissured coal specimens. Only research on mechanical tests of rock or rock-like fissured specimens was retrieved. The numerical results were compared with the laboratory results in this published paper of rock-like material specimens with various angle fissure specimens, as presented in Figure 4 [41, 45]. The failure modes of three numerical specimens are similar to those obtained by the experiment, so the numerical model can be safely used.

4. Modeling Results

4.1. Coal Burst Proneness Characteristics of Various Fissure Configurations

4.1.1. Single Fissure Coal Specimens. The crack distribution of single fissure coal specimens when loaded to the peak strength and complete destruction is shown in Figures 5
and 6. Crack propagation patterns in coal specimens were different for various inclination angles. When loaded to peak strength, scattered microcracks randomly distributed across the specimens with inclination angles $\beta = 0^\circ$ and $90^\circ$, whereas macrocracks initiated from the fissure tip and propagated along the loading direction for other inclination angles conditions. Macrocracks propagated to the loading boundary for $\beta = 30^\circ$, and the macrocrack length decreased as the inclination angle $\beta$ deviated from $30^\circ$. The elastic strain energy was able to easily accumulate in the microcracks or short macrocracks. Such an observation was more evident in the coal specimens with inclination angles at $0^\circ$ and $90^\circ$. By contrast, sliding failure tends to occur in the long macrocracks, leading to a significant consumption of energy. Such an observation was more evident in the coal specimens with inclination angles other than $0^\circ$ and $90^\circ$.

After being loaded to complete destruction, enormous cracks were observed after the peak strength, and they transformed into macroscopic cracks, leading to the complete destruction of the specimen. Vertical macrocracks across the specimens could be observed for inclination angles $\beta = 0^\circ$ and $90^\circ$, while macrocracks propagated from the fissure tip and along the loading direction for other inclination angles.

Differences in the crack propagation patterns subjected to various testing conditions were associated with mechanical behavior and burst proneness. The stress–strain curves and coal burst proneness with different inclination angles are illustrated in Figures 7 and 8, respectively. The changing trends of UCS, ESE and REI were similar. These three parameters initially decreased as the inclination angle increased from $0^\circ$ to $30^\circ$, following by increasing as the inclination angle increased from $30^\circ$ to $90^\circ$.

4.1.2. Two Non-coplanar-Parallel Fissure Coal Specimens. After two non-coplanar-parallel fissure coal specimens were loaded to the peak strength and complete destruction,
similar results were observed, as shown in Figures 9 and 10. When loaded to peak strength, scattered microcracks randomly distributed across the specimens for inclination angles $\beta = 0^\circ$ and $90^\circ$, whereas macrocracks initiated from the fissure tip and propagated along the loading direction for other inclination angles. For $\beta = 30^\circ$, $45^\circ$, and $60^\circ$, two fissures were connected by microcracks.

After loading to complete destruction, enormous cracks were observed after the peak strength, and they transformed into macroscopic cracks, leading to the complete destruction of the specimen. Vertical macrocracks across the specimens could be observed for inclination angles $\beta = 0^\circ$ and $90^\circ$, while macrocracks propagated from the fissure tip and in the loading direction for other angles.

The stress–strain curves and coal burst proneness with different inclination angle are illustrated in Figures 11 and 12. The influence of the inclination angle on UCS, ESE, and REI was similar. These three parameters decreased initially as the inclination angle increased from $0^\circ$ to $30^\circ$, and then increased as the inclination angle increased from $30^\circ$ to $90^\circ$.

4.1.3. Two Coplanar-Parallel Fissure Coal Specimens. After two coplanar-parallel fissure coal specimens were loaded to the peak strength, the crack distribution was observed, as shown in Figure 13. For $\beta = 0^\circ$ and $90^\circ$, scattered microcracks randomly distributed across the specimens. For $\beta = 15^\circ$, two short macrocracks initiated from the tips of the left fissure. For $\beta = 30^\circ$, four long macrocracks initiated from the tips of two fissures and propagated in the loading direction. For $\beta = 45^\circ$ and $60^\circ$, two fissures were connected by microcracks, and macrocracks initiated from the outside tips of the two fissures and propagated in the loading direction. For $\beta = 75^\circ$, two fissures were connected by microcracks, and a short macrocrack initiated from the lower tip and propagated in the loading direction.

The elastic strain energy could easily accumulate in the microcracks or short macro-
cracks. Such an observation was more evident in the coal specimens with inclination angles at 0° and 90°. By contrast, sliding failure tends to occur in the long macrocracks, leading to a significant consumption of energy. Such an observation was more evident in the coal specimens with inclination angle other than 0° and 90°.

After two coplanar-parallel fissure coal specimens were loaded to complete destruction, the crack distribution was observed, as shown in Figure 14. For β = 0° and 90°, vertical macrocracks across the specimens could be observed. For β = 15°, macrocracks formed a “Y” shape and one vertical macrocrack penetrated into the lower part of specimen from the middle area of the two fissures. For β = 30°, two vertical macrocrack penetrated the entire specimen from the tips of the right fissure and one vertical macrocrack penetrated into the upper part of specimen from the upper tip of the left fissure. For β = 45°, 60°, and 75°, oblique macrocracks were formed across specimens.

The stress–strain curves and coal burst proneness with different inclination angles are illustrated in Figures 15 and 16. The influence of the inclination angle on the UCS, ESE and REI were similar. All these three parameters tended to decrease as the inclination angle increased from 0° to 30°; then, they would increase as the inclination angle increased from 30° to 90°.

4.2. Coal Burst Proneness Comparison with Various Fissure Configurations. Coal burst proneness indicators, ESE and REI, of different fissured specimens are compared in Figure 17.

4.2.1. For β = 0°, 15°, 30°, and 90°. The magnitude of the ESE index in the condition of two coplanar-parallel fissures was greater than that in the condition of a single fissure, and the value of this parameter was smallest in the condition of two non-coplanar-parallel fissures. The magnitude of REI index in the condition of a single fissure was greater than...
that in the condition of two coplanar-parallel fissures, and the value of this parameter was smallest in the condition of two non-coplanar-parallel fissures. The evaluation results of the ESE and REI indexes were contrary to each other for a single fissure and two coplanar-parallel fissures, and so the residual energy (RE), calculated by Equation (2), was further used for coal burst proneness evaluation. The results are shown in Table 3. The magnitude of the RE index in the condition of two coplanar-parallel fissures was greater than that in the condition of a single fissure, and the value of this parameter was smallest in the condition of two non-coplanar-parallel fissures.

4.2.2. For $\beta = 45^\circ, 60^\circ, \text{ and } 75^\circ$. The trends of the two coal burst proneness indexes, ESE and REI, were consistent with each other, and so the coal burst proneness in the condition of two coplanar-parallel fissures was greater than that in the condition of a single fissure, whereas the coal burst proneness is lowest in the condition of two non-coplanar-parallel fissures.

In summary, the coal burst proneness in the condition of two coplanar-parallel fissures was greater than that in the condition of a single fissure, whereas the coal burst proneness was lowest in the condition of two non-coplanar-parallel fissures.

5. Mechanism Analysis of Coal Burst Proneness with Various Fissure Configurations

5.1. Analysis of the Crack Initiation Stress $\sigma_{ci}$. The instability and damage of roadways surrounding rocks are caused by the initiation-expansion-penetration of the internal cracks. Crack initiation marks the beginning of crack development and expansion, and also marks the beginning of macroscopic damage. The stress at the moment when the new crack is generated is determined as the crack initiation stress. The greater the crack initiation stress, the less likely the rock mass to be damaged, and the higher the energy accumulated before the failure. The initiation of primary cracks is an important factor affecting coal strength and underground engineering stability. The ratio of the crack initiation stress to the peak stress of the coal mass, that is, the crack initiation stress level, is an important index to determine the difficulty of cracking. The higher the crack initiation stress, the higher the accumulated elastic strain energy is, the more severe the damage under the action of high elastic energy is, and the stronger the coal burst proneness is. Therefore, the crack initiation stress of the fissured coal mass has an important influence on the coal burst proneness.

Table 4 summarizes the crack initiation stress and crack initiation stress levels for the three types of fissured specimens. Taking single fissure specimens as an example for analysis, when the fissure inclination angle is $0^\circ$ and $90^\circ$, the crack initiation stress is higher, and the crack initiation stress is 46% and 42% of the peak stress. This kind of coal specimen ruptures under lower load, and the coal specimen ruptures gradually, meaning the crack growth rate is relatively slow. Overall, with the increase in the fissure

<table>
<thead>
<tr>
<th>$\beta$ ($^\circ$)</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>90</th>
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<tr>
<td>Single fissure specimens</td>
<td>30.56</td>
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<td>13.44</td>
<td>29.78</td>
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<tr>
<td>Two coplanar-parallel fissure specimens</td>
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<td>20.16</td>
<td>14.56</td>
<td>30.42</td>
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<tr>
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<td>11.68</td>
<td>7.36</td>
<td>29.56</td>
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</tbody>
</table>

Figure 17: Comparison of different fissured specimens for coal burst proneness: (a) ESE index and (b) REI index.

Table 3: Coal burst proneness evaluation using RE for the three types of fissured specimens ($10^3$/m$^3$).
Table 4: Summary of crack initiation stress for three types of fissured specimens.

<table>
<thead>
<tr>
<th>$\beta$ (°)</th>
<th>Single fissure specimens</th>
<th>Two coplanar-parallel fissure specimens</th>
<th>Two non-coplanar-parallel fissure specimens</th>
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<tbody>
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<td>$\sigma_p/\sigma_q$</td>
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<td>7.81</td>
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<td>3.26</td>
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</tbody>
</table>

Inclination angle, the crack initiation stress and the crack initiation stress level first decreased and then increased, and were lowest at 45°, which was basically consistent with the change rule of the coal burst proneness of single fissure specimens. It is worth noting that crack initiation stress is lowest for the 45° fissure specimen, while the coal burst proneness is still higher than that of the 30° fissure specimen. Since the stress peak and prepeak elastic strain energy for the 30° fissure specimen are lower than those for the 45° fissure specimen, even though the 45° fissure specimen has the lowest crack initiation stress, the coal burst proneness is still higher than that of the 30° fissure specimen on the basis of the relatively high elastic strain energy.

The variation rule of crack initiation stress with the inclination angle of the two coplanar-parallel fissure specimens and the two non-coplanar-parallel fissure specimens are similar to that of the single-fissure specimens. Compared with the single-fissure specimens, the two coplanar-parallel fissure specimens have higher crack initiation stress and crack initiation stress levels, and the specimens accumulate higher energy and rupture more rapidly. Compared with the single-fissure specimens, the two non-coplanar-parallel fissure specimens have lower crack initiation stress and crack initiation stress levels, and the specimens accumulate lower energy and rupture more slowly. Therefore, the magnitude of crack initiation stress and crack initiation stress levels in the condition of two coplanar-parallel fissures was greater than that in the condition of single fissure, and the value of this parameter was smallest in the condition of two non-coplanar-parallel fissures. The rules are basically consistent with the coal burst proneness, which further indicates that the crack initiation stress has an important influence on the coal burst proneness.

5.2. Analysis of Elastic Strain Energy Distribution. The elastic strain energy is a significant contributing factor in bursting [20], so the study of strain energy distribution is very necessary. Fissures in coal are closely related to the distribution of stress and elastic strain energy of coal mass, and the strain energy distribution characteristics of fissured coal are helpful to study the coal burst proneness [46]. Figure 18 shows the elastic strain energy distribution of specimens with different fissure when loaded to peak strength. Figure 18(a) shows the distribution of elastic strain energy at different inclination angles of the single-fissure specimens. For inclination angles $\beta=0°$ and $90°$, uneven red spot-like high-energy regions formed on the specimen surface, and the overall distribution density of high elastic strain energy was higher than that of specimens with other inclination angles, indicating that higher levels of elastic strain energy were accumulated. For the inclination angle $\beta=15°$, an uneven red spot-like high-energy area was formed on the surface of the specimen, but the distribution density of the high strain energy of the uneven red spot was lower than that of the specimens with inclination angles $\beta=0°$ and $90°$. At both fissure ends, densely distributed red high strain energy spots were formed, and the overall elastic strain energy of the specimen was lower than $0°$ and $90°$. For inclination angle $\beta=30°$, macrocracks generated at both ends of the fissure propagated to loading boundaries, and the elastic strain energy value accumulated on the inner side of the two penetration cracks was very low, forming a low-energy area. The high energy value of elastic strain accumulated on the outside of the two penetrating cracks, formed a high-energy region, and the energy concentration region was at the end of the fissure. As the inclination angle increased from $30°$ to $75°$, the length of the secondary macrocracks gradually shortened, the range of the low-energy region gradually decreased, and the range of the high-energy region gradually increased. When the fracture inclination angle was $75°$, there was only a very small region of low elastic strain energy. From the perspective of the distribution of elastic strain energy, with the increase in the crack inclination angle, the elastic strain energy first decreased and then increased, and it was lowest when the fissure inclination angle was $30°$. The strain energy accumulated at a fissure dip angle of $30°$ is the lowest, which is consistent with the change rule of the coal burst proneness of a single-fracture coal body.

The distribution of elastic strain energy of the two coplanar-parallel fissure coal specimens and that of the two non-coplanar-parallel fissure coal specimens with the various inclination angles were similar. The three groups of specimens corresponding to fissure inclination angles of $0°$ and $90°$ had no obvious differences in terms of elastic strain energy distribution. After comparing the specimens with other inclination angles, it was found that there were a energy concentration area between two fissures and a smaller low-energy area in the loading direction for the
two coplanar-parallel fissure coal specimens, as shown in Figure 19(a). Therefore, the two coplanar-parallel fissure coal specimens accumulate higher elastic strain energy and have a stronger coal burst proneness than the single fissure coal specimens. In the two non-coplanar-parallel fissure coal specimens, a relatively low-strength elastic body was formed between the two fissures, which made it form a larger area of low elastic strain energy along the loading direction, and the elastic strain energy value decreased at the same time, as shown in Figure 19(c). Therefore, the two non-coplanar-parallel fissure coal specimens accumulate lower elastic strain energy and has a relatively weaker coal burst proneness than the single fissure coal specimens. The rules are consistent with the coal burst proneness, which further indicates that the elastic strain energy distribution has an important influence on the coal burst proneness.

6. Conclusions

In this paper, the energy transformation processes of various fissured coal specimens under uniaxial compression loading were analyzed based on the stress–strain curves. The elastic

![Energy distribution comparison](image)

**Figure 18:** Elastic strain energy distribution comparison of different fissured specimens when loading to peak strength: (a) single fissure coal specimens; (b) two coplanar-parallel fissure coal specimens; (c) two non-coplanar-parallel fissure coal specimens.

![Energy concentration area](image)

**Figure 19:** Comparison of energy distribution characteristics for different types of fissured specimens ($\beta = 45^\circ$): (a) two coplanar-parallel fissures; (b) single fissure; (c) two non-coplanar-parallel fissures.
strain energy (ESE) and residual energy index (REI) were used as evaluation indexes for coal burst proneness after comparing with other indicators. The coal burst proneness of fissured coal mass was investigated by means of the calibrated PFC$^{2}$D model of fissured coal specimens. Through the simulated results, the following conclusions can be summarized:

(1) For the three types of fissured specimens, the influence of the inclination angles on the uniaxial compressive strength (UCS), ESE, and REI was similar. These parameters tend to decrease initially as the inclination angle increases from $0^\circ$ to $30^\circ$, followed by increasing as the inclination angle increases from $30^\circ$ to $90^\circ$. Through the coal burst proneness comparison of various fissure configurations, it is found that the coal burst proneness in the condition of two coplanar-parallel fissures was greater than that in the condition of a single fissure, whereas the coal burst proneness was lowest in the condition of two non-coplanar-parallel fissures.

(2) The crack initiation stress of coal mass is closely related to elastic strain energy and then affects the failure severity and burst proneness of coal mass. With the increase in the fissure inclination angle, the crack initiation stress and the crack initiation stress level first decreased and then increased and were lowest at $45^\circ$. For various fissure configurations, the magnitude of crack initiation stress and crack initiation stress levels in the condition of two coplanar-parallel fissures was greater than that in the condition of a single fissure, and the value of this parameter was the lowest parameter in the condition of two non-coplanar-parallel fissures, which was basically consistent with the change rule of the coal burst proneness.

(3) From the perspective of the distribution of elastic strain energy, with an increase in the crack inclination angle, the elastic strain energy first decreases and then increases, and it is lowest when the fissure inclination angle is $30^\circ$, which is consistent with the change rule of the coal burst proneness of a single fracture coal body. The two coplanar-parallel fissure coal specimens have an energy concentration area between two fissures and a smaller low-energy area in the loading direction. Meanwhile, in the two non-coplanar-parallel fissure coal specimens, a relatively low-strength elastic body is formed between the two fissures, which causes it to form a larger area of low elastic strain energy along the loading direction. Therefore, the elastic strain energy in the condition of two coplanar-parallel fissures was greater than that in the condition of a single fissure, whereas the coal burst proneness in the condition of two non-coplanar-parallel fissures was lowest, which further indicates that the elastic strain energy distribution has an important influence on the coal burst proneness.

(4) These results can be used as a guideline for forecasting and preventing coal burst. For example, cracks with an inclination angle of $30^\circ$ that might lead to stress concentration in the rock/coal mass should be preconditioned by hydraulic fracturing technology to reduce the risk of coal burst. In this study, coal burst proneness levels could not be determined due to the limitation of the number of laboratory tests on the coal specimens. It is recommended that more UCS tests be conducted on the various fissured coal specimens to further evaluate the level of coal burst proneness.

(5) This study established the burst proneness characteristics of different types of fissures from the theoretical view. The fissures’ distribution of the specimen can be simplified into three types of units. The combination of different fissure units could stand for the actual fissure distribution. The coal burst proneness of coal mass will be studied from the perspective of the system including many fissured units in the future. Also, the coal burst proneness with different fissure distributions is different, which can guide the prediction and prevention of coal burst.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declared that they have no conflicts of interest in this work. The data analysis and manuscript were finished by the first author Zhijie Zhu. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Authors’ Contributions

Zhijie Zhu was responsible for the conceptualization, formal analysis, data curation, visualization, and writing of the original draft. Zhenhua Yao was responsible for the software used and writing of this paper. Jan Nemcik and Laigui Wang were responsible for the supervision and conceptualization of the paper and the software used and the writing, review, and editing of the manuscript. Jun Han and Lihai Tan were responsible for the supervision and conceptualization of the paper.

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