

Article

# Analysis of Energy Accumulation and Dissipation of Coal Bursts

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Received: 2 July 2018; Accepted: 10 July 2018; Published: 11 July 2018



**Abstract:** Coal bursts are a serious dynamic hazard for underground coalmines, and they attract the extensive interest of studies from mining and geotechnical researchers worldwide. More recently, coal-burst incidents were reported in some Australian coalmines as a result of inadequate geological assessment of coal-burst hazards. The coal-burst process is closely associated with the accumulation of elastic energy and the rapid dissipation of kinetic energy. This paper introduces the essential geological conditions for energy accumulation, and the likely precursors for rapid energy dissipation leading to coal burst, which can be used by Australian coalmines to determine their coal-burst risk accordingly. Different energy forms and their transformations during the coal-burst process are introduced in detail in this paper. The dominant geological factors resulting in the accumulation of massive energy are analyzed, and the likely precursors associated with the instant release of elastic energy are discussed.

**Keywords:** coal burst; energy; mine hazards; underground mining

## 1. Introduction

The violent and catastrophic failure of coal, named “coal burst” in underground mining, can release a large amount of energy in the forms of acoustic emission, mine seismicity, and coal ejection. The long history of coal bursts in Poland, Russian, the United States (US), and China is well-documented [1,2]. It is illustrated by the mining experience of these countries that both the frequency and the severity of coal bursts increase with mining depth. There are no recorded coal-burst accidents in Australia before 2014, as Australian coalmines are generally characterized by shallow mining depths, simple geological conditions, advanced mining technology, and reasonable geotechnical design. However, following the four coal-burst accidents, happening in 2014 [3], 2016 [4], 2018 [5], and 2018 [6], it is consequently believed by researchers and engineers that Australian coalmines will face the safety hazards caused by coal bursts going forward.

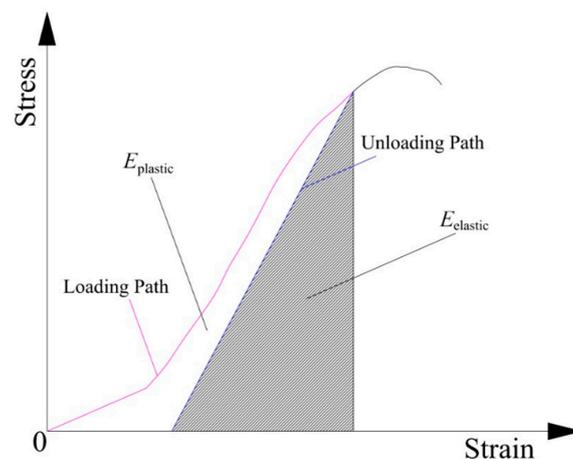
Thorough research was conducted over decades on the potential driving mechanism of coal bursts, and on technologies aimed at solving associated problems. There are many hypothesized mechanisms of coal burst discussed by researchers, arising from various aspects including stress [7], stiffness [8], energy [9], and coal properties [10]. Advanced techniques, such as hydraulic fracturing [11], destress blasting [12], and water infusion [13,14], are adopted in coalmines to mitigate the risk of coal bursts. These theories and technologies may be able to explain the formation of coal burst, or may be able to

diminish the damage of potential coal-burst accidents following the first recognized case of coal burst accident at a coalmine. However, the risk of coal burst is generally hard to recognize for coalmines with no history of coal burst. Particularly in Australian coalmines, coal-burst hazards are hard to recognize, as there is no pre-assessment process or real-time monitoring apparatus of coal-burst risk.

Energy concepts associated with coal bursts are a hotspot of coal-burst research. Based on the mechanical behavior of coal subject to uniaxial compression stress, Bieniawsk et al. found that coal bursts only happen when a large amount of elastic energy is stored in the body of coal [15]. Many researchers carried out detailed research on the energy dissipation forms of coal bursts, and proposed various coal-burst monitoring and early-warning methods, such as electromagnetic radiation [16], acoustic emission [17], and microseismic techniques [18–20]. L.M. Dou believes that the key to mitigating coal bursts is a decrease in the elastic energy stored in the coal or surrounding rock of the mining area [21]. In other words, coal bursts only happen when massive elastic energy stored in the coal is instantaneously released. This paper aims to introduce the essential geological conditions for energy accumulation, and the likely precursors for rapid energy dissipation in coalmines, which can assist Australian coalmines in determining their coal-burst risk accordingly. To achieve this aim, various energy forms and energy balances featured during coal bursts are introduced in detail. Then, the dominant geological factors resulting in the accumulation of massive energy are analyzed. Furthermore, the likely precursors associated with the instant release of elastic energy are discussed.

## 2. Energy Forms and the Energy Conservation Equation

Coal bursts are described as an energy phenomenon accompanying coal deformation and fracture, in the form of brittle and violent failure induced by mining [22]. The energy consumed by coal exists in various forms, and only a part of the total energy can lead to personal casualties or equipment damage. In the context of material science, coal is classified as an elastic/plastic material. Hence, as shown in Figure 1, Kidybiński divided the energy consumed by coal before peak strength into two parts: elastic energy ( $E_{\text{elastic}}$ ) and plastic energy ( $E_{\text{plastic}}$ ). He also believed that elastic energy is related to coal bursts following the irreversible consumption of plastic energy during the unrecoverable deformation and fracture of coal. Most researchers accept this deduction, as it was proven via laboratory tests [23] and through mining experience [21] that coal bursts only happen in coal seams with a high elastic energy. The  $E_{\text{elastic}}/E_{\text{plastic}}$  ratio consequently became a widely adopted indicator for the evaluation of coal-burst liabilities [24,25]. Elastic energy, transformed into kinetic energy, can manifest itself in ejected coal, leading to fatal accidents [9,26]. However, it was found in experimental research on granite samples that the kinetic energy carried by ejected rock particles only accounts for no more than 1% of the elastic energy stored before peak strength [27]. That is, a large amount of elastic energy is dissipated into other forms during the gentle failure of rock.



**Figure 1.** Schematic diagram of the elastic and plastic energies of coal subjected to a compression load.

It was found by researchers that rich acoustic signals were detected at the failure points of concrete and rock materials [28–30]. A similar phenomenon also happened during the failure process of coal [31]. Many scholars conducted detailed studies on the mechanism underlying the acoustic emission of geo-materials [29,30,32,33]. It was found by researchers that the acoustic emission of geo-materials is positively related to the material's fracture and deformation. A reasonably good correlation between fracture energy ( $E_{\text{fracture}}$ ) and acoustic-emission energy ( $E_{\text{acoustic}}$ ) was found by Landis on mortar specimens [28]. Shkuratnik et al. found that acoustic emission is positively related to the compression stress applied to a coal sample [34,35]. A uniaxial compression test of an Australian coal sample, conducted by Ranjith et al. also led to the same conclusion as that of Shkuratnik [31]. Figure 2 describes the acoustic-emission signals detected in our laboratory during the loading process of tension failure applied to a coal sample. As shown in the figure, rich acoustic emission signals were received by the acoustic-emission monitoring system. Hence, coal and other geo-materials release a large amount of fracture energy at the failure point. This energy is consumed by the growth of the microfracture [17]. It was pointed out by some researchers that geo-materials receive no energy input from outside the failure point [36]. Therefore, the fracture energy dissipated at the failure point arises from the internal elastic energy stored in coal, which also explains why kinetic energy accounts for no more than 1% of total elastic energy. Furthermore, other energy dissipation forms, including electromagnetic-emission energy ( $E_{\text{em}}$ ), microseismic energy ( $E_{\text{seismic}}$ ), and thermal-radiation energy ( $E_{\text{thermal}}$ ), are also positively related to fracture energy [16–18,37–39]. It is worthy of note that all these forms of energy correspond to the energy dissipation at, and just after, the failure point of coal.

During coal bursts, the movement of ejected coal consumes elastic energy, termed coal-ejection energy ( $E_{\text{ejection}}$ ). Some of the elastic energy may remain stored in the coal even after the coal burst, which is herein referred to as residual energy ( $E_{\text{residual}}$ ). Hence, the conservation of elastic energy during coal bursts can be represented by the following equation:

$$E_{\text{elastic}} = E_{\text{ejection}} + E_{\text{fracture}} + E_{\text{acoustic}} + E_{\text{em}} + E_{\text{seismic}} + E_{\text{thermal}} + E_{\text{residual}}. \quad (1)$$

Generally, the accumulation of elastic energy results from gravitational stress ( $E_{\text{gravity}}$ ), tectonic stress ( $E_{\text{tectonic}}$ ), concentrated stress ( $E_{\text{concentrated}}$ ), and dynamic stress ( $E_{\text{dynamic}}$ ) [9,40]. Hence, the complete balanced equation for energy in an underground coal body can be written as follows [40]:

$$E_{\text{gravity}} + E_{\text{tectonic}} + E_{\text{concentrated}} + E_{\text{dynamic}} = E_{\text{elastic}} + E_{\text{plastic}}. \quad (2)$$

During the gentle failure of coal, most of the elastic energy dissipates into other forms of energy, excluding that of coal ejection. Coal can be ejected from the surrounding areas of underground space, forming burst hazards when its energy is high enough.

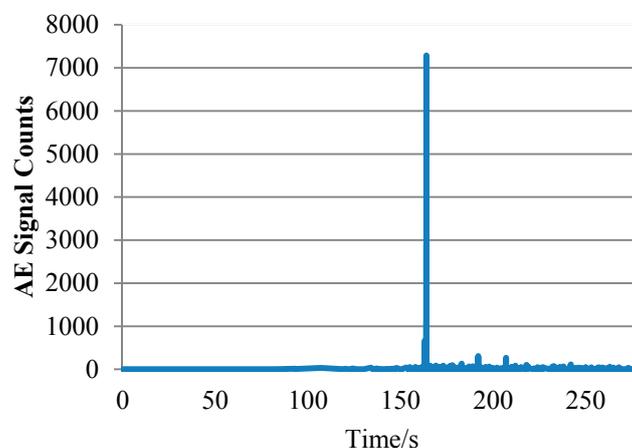


Figure 2. AE (Acoustic Emission) signal of the tensile failure in coal.

### 3. Energy Accumulation

The energy accumulation of coal bursts is dominated by specific geological conditions such as mining depth, roof and floor stiffness, seismicity events, and coal properties. It was found by Kelly that many coal-mining projects in Australia have inadequate or incorrect geological assessments [7]. An explanation of the contribution of these factors to the accumulation of elastic energy can be helpful for Australian coalmines to evaluate the risk of coal bursts occurring, according to their geological conditions.

#### 3.1. Mining Depth

An increase in the severity and frequency of coal bursts with mining depth was found by researchers worldwide [1,7,41,42]. Mining depth can directly contribute to the increase in risk of coal bursts from two aspects. Firstly, coal is under high gravitational stress, and becomes more prone to failure as gravitational stress increases with mining depth. Additionally, the high gravitational stress results in more energy being introduced into the body of coal. The mechanical properties of coal resources with a large mining depth are more brittle and more prone to burst. The geological features associated with deep mining are more complicated, and are also often related to hard sandstone roofs [7], which can further result in a large accumulation of energy in the geological structure. According to an investigation based on documented cases of coal burst in Poland, Russian, and China, the risk of coal burst increases sharply when the mining depth extends beyond 500 m [43]. The mining depths of the Appin coalmine and the Austar coalmine (the sites of two incidents of coal burst in Australia) are both around 550 m [3]. However, it should be noted that coal bursts can also occur at shallow depths if the stored energy in the coal seam is high enough, which is often related to complicated geological structures such as faults and folds.

#### 3.2. Stiffness

Stiffness of the roof and floor is one of the main factors giving rise to coal bursts [42]. An experimental study also proved that surrounding rock stiffness had an obvious influence on the failure mode of a coal sample [44]. The influence of the surrounding rock stiffness on coal bursts was deduced based on mining experience and laboratory studies. Generally, coal tends to fail violently when the stiffness of the roof and floor is high. A theoretical explanation of the influence of stiffness can be easily derived from the energy aspects. The definition of stiffness is given as

$$K = F/L, \quad (3)$$

where  $K$  is stiffness of the material,  $F$  is the compression force applied to the material, and  $L$  is the displacement caused by the applied force.

According to Newton's third law, the force between the roof and the floor has the following relationship:

$$F_{\text{roof}} = F_{\text{coal}}, \quad (4)$$

where  $F_{\text{roof}}$  is the force applied to the coal seam by the roof, and  $F_{\text{coal}}$  is the reaction force given to the roof by the coal.

In terms of the roof, the energy input from the coal can be described as

$$E_{\text{roof}} = F_{\text{coal}} \times L_{\text{roof}}, \quad (5)$$

where  $E_{\text{roof}}$  is the energy flowing from the coal to the roof, and  $L_{\text{roof}}$  is the displacement caused by  $F_{\text{coal}}$ .

In terms of the coal seam, the energy input from the roof can be described as

$$E_{\text{coal}} = F_{\text{roof}} \times L_{\text{coal}}, \quad (6)$$

where  $E_{\text{coal}}$  is the energy flowing from the roof to the coal, and  $L_{\text{coal}}$  is the displacement caused by  $F_{\text{roof}}$ .

In most cases, the stiffness of the roof is higher than that of the coal:

$$K_{\text{roof}} > K_{\text{coal}}, \quad (7)$$

where  $K_{\text{roof}}$  is the stiffness of the roof, and  $K_{\text{coal}}$  is the stiffness of the coal.

Consequently, the displacement of the coal is larger than that of the roof:

$$L_{\text{coal}} > L_{\text{roof}}. \quad (8)$$

Hence, the final flow of energy flow goes from the roof to the coal:

$$E_{\text{coal}} > E_{\text{roof}}. \quad (9)$$

Based on the above analysis, the direction of energy flow between the coal and the roof is controlled by their difference in stiffness. As the difference in stiffness between the coal and the roof increases, so too will the amount of energy flowing into the coal seam. This also explains why a hard roof presents a tricky problem for coalmines, as more energy will be transferred from the roof to the coal under these conditions. Similarly, the stiffness of the floor also has the same influence on coal. As shown in Figure 3, a high stiffness of the surrounding rock can lead to sudden and violent uncontrolled post-failure behavior [42].

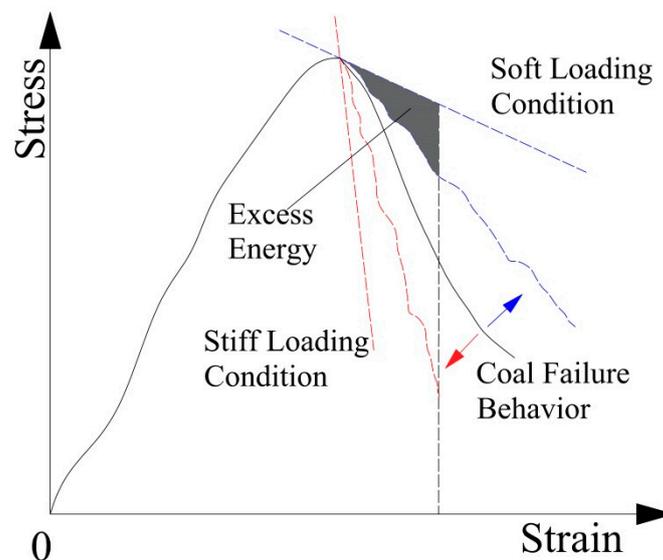


Figure 3. Effect of stiffness of the loading system on the behavior of coal failure.

### 3.3. Seismicity

Seismicity is a common phenomenon associated with mining and tunneling activities. As shown in Figure 4, seismic waves, which are released by artificially triggered or naturally induced seismicity, can introduce a surprisingly high level of stress on the coal in a very short time. Hence, massive seismic energy is transferred to the coal. Furthermore, it is clear that the stress-bearing ability and the energy-storage capacity of coal are positively correlated to the loading rate [45,46]. Therefore, coal bursts resulting from seismicity events are more dangerous and destructive. A detailed explanation of coal bursts under superposition of seismicity (dynamic load) and geo-stress (static load) was given by L.M. Dou [47]. An observation of the seismic events in areas featuring occurrences of coal bursts revealed that Australian mines experience a significantly lower frequency of seismic activity compared to that of coalmines worldwide [48], which may explain why the coal bursts appear less devastatingly in Australia.

### 3.4. Elasticity

Coal seams have different mechanical behavior in response to the same loading path, due to differences in physical and chemical properties. As introduced above, it was found that coal bursts often occur in coal seams with high elastic energy. Hence, the good elasticity of coal contributes to the formation of coal bursts. Our laboratory tests also found that coal seams which have a history of coal bursts show good elastic behavior. Some coal samples were collected from New South Wales and central Queensland in Australia. Sample 1 and Sample 2 were from a Bulli seam in New South Wales, which is 550 m in depth. The coal burst at the Appin coalmine occurred in Bulli seam. Sample 3 and Sample 4 were from a coal seam with a depth of 250 m. All samples were cut and ground into pieces of 50-mm diameter and 100-mm length, before being subjected to a cyclic loading path with a control loading rate featuring a displacement of 0.1 mm/min. As shown in Figure 5, the elastic energy accounted for a larger percentage during the loading processes of Sample 1 and Sample 2. Furthermore, the post-failure behaviors of Sample 1 and Sample 2 were gentler and less brittle. To evaluate the elastic behavior of coal seams, various indices and methods were put forward by scholars. The coal-burst propensity index, which includes four indices proposed by Russian, Polish, and Chinese scholars, is a widely adopted method of evaluating the elasticity of coal [10,23]. It is recommended by many researchers worldwide that the elasticity of coal seams should be evaluated to determine the risk of coal burst prior to commencing extraction of a new long-wall face.

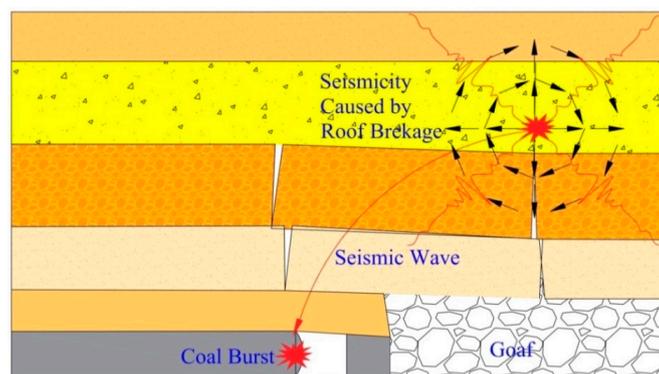


Figure 4. Influence of a dynamic load caused by seismicity on a coal burst [49].

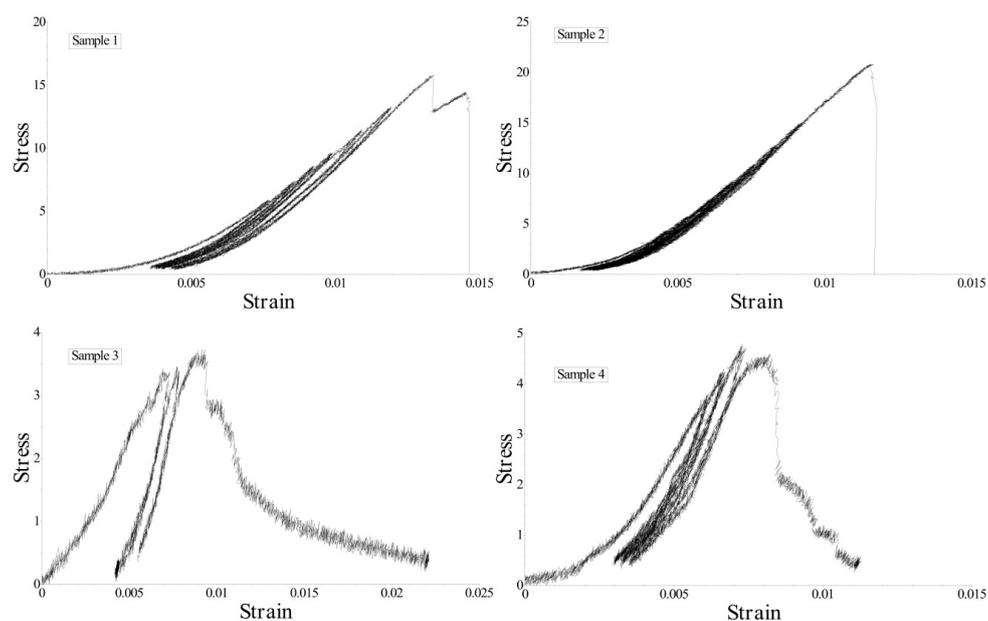


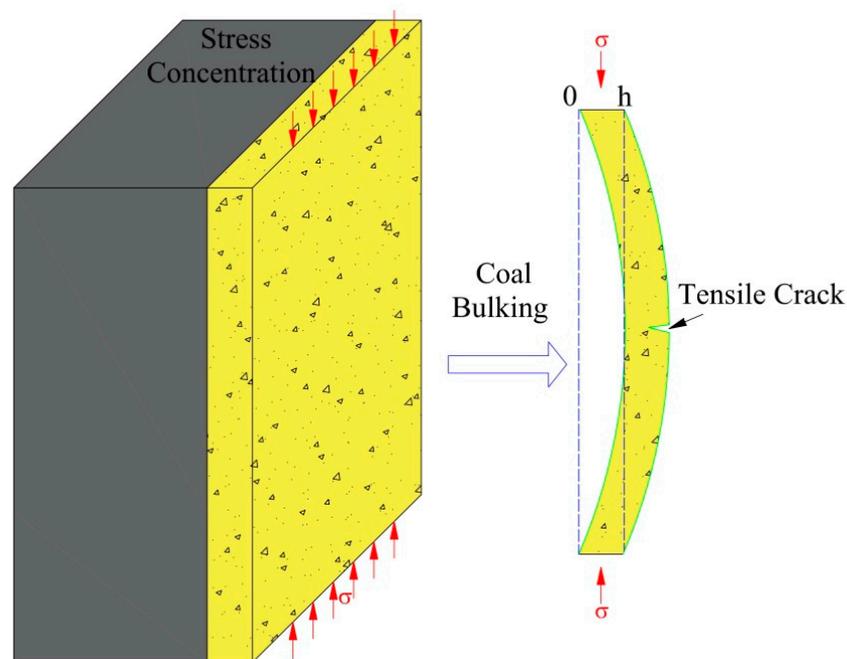
Figure 5. Strain–Stress curves of coal samples subjected to cyclic loading.

#### 4. Energy Dissipation

Some phenomena may be likely precursors of the catastrophic failure of coal prior to the occurrence of coal bursts, which can potentially serve to mitigate the associated hazards.

##### 4.1. Bulking

Massive ejected bodies of coal with high kinetic energies can lead to equipment damage and personal injury. The double fatalities which happened at the Austar coalmine in Australia were caused by ejected coal [3]. Coal ejections due to coal bursts generally last a very short time, during which massive kinetic energy is released. However, as a heterogeneous and nonlinear geo-material, coal may feature a concentration of stress in naturally occurring areas of structural weakness. As shown in Figure 6, solid coal with areas of weakness bulk due to the concentration of stress. Small-scale coal splits can even happen in these areas if the stored energy is large enough. Generally, before the dynamic failure of coal, bulking begins to appear, or an abnormal increase in area is observed.



**Figure 6.** Schematic diagram of coal bulking caused by a concentration of stress.

##### 4.2. Acoustic Events

It was found by scholars that acoustic, electromagnetic, and microseismic events are positively associated with cracks in solid materials [16,17,20]. In particular, prior to the dynamic and disastrous failure of coal, the frequency and magnitude of these events increase sharply. Most of these phenomena can only be observed and detected using specific and advanced monitoring equipment. Many coalmines identified as having a high risk of coal bursts in Poland, China, and the US adopt various types of equipment to monitor coal fractures. However, the installation and maintenance costs of monitoring equipment are considerably high. The training process of a forecasting model is also time-consuming. Most coalmines in Australia have no available equipment for the monitoring of coal fractures at this point in time. Although most acoustic signals are inaudible without the use of specific sensors, the acoustic events associated with large-scale solid coal fractures can sometimes be heard by the human auditory system. Many mining engineers and workers mention that the dreary sound of coal cracks can be heard in coalmines with concentration of high stress and energy.

## 5. Conclusions

Coal bursts are the catastrophic failures of underground coal, which are closely associated with violent and instant releases of energy. This paper tried explaining the necessary formation conditions and likely precursors of coal bursts in the context of energy. The accumulation and dissipation of energy during coal bursts were analyzed. Based on the analysis, the following conclusions can be drawn:

1. Generally, destruction and safety hazards are caused by ejection energy, as a result of the transformation of elastic energy. The accumulation of elastic energy in coal is dominated by geological conditions, such as mining depth, surrounding rock stiffness, seismicity events, and its mechanical properties. Mining depth and seismicity events are sources of energy caused by static loads and dynamic loads, respectively. The influence of these factors on the accumulation of elastic energy was established through energy analysis.
2. According to the analysis of stiffness, energy flows from the surrounding rock (high stiffness) to the coal (low stiffness). Hence, for coalmines with stiff roofs and floors, the elastic energy tends to concentrate in the coal seam.
3. The elasticity of coal is determined by its capacity and ability to store elastic energy. It is recommended from our laboratory tests that the ability of coal seams to store elastic energy should be evaluated using the coal-burst propensity index prior to commencing the extraction of long-wall faces or roadways. Australian coalmines can determine their potential risk of coal bursts according to the results of the coal-burst propensity evaluation and other geological conditions.
4. Some audible or visible phenomena, such as bulking and acoustic events, may appear prior to the occurrence of coal bursts. These phenomena indicate a concentration of high energy in the body of the coal, suggesting the possibility of coal bursts in the near future.

**Author Contributions:** The completion of this paper was contributed to by all authors. Writing—original draft and preparation, X.Y. Writing—review and editing, T.R., X.H. and L.T. Supervision, A.R.

**Funding:** This research is supported by ARC Industrial Transformation Research Hub for Nanoscience-based Construction Material Manufacturing (IH150100006).

**Acknowledgments:** The first author would like to express sincere appreciation for the funding provided by the China Scholarship Council (201606420052) and the International Postgraduate Tuition Award (IPTA) of the University of Wollongong.

**Conflicts of Interest:** The authors declare no conflict of interest.

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