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Chapter

Coal Burst: A State of the Art on Mechanism and Prevention from Energy Aspect

Xiaohan Yang

Abstract

Coal burst continues to be one of the most catastrophic safety hazards faced by future mining as the stress environment will be more complicated with the increase of mining depth. Many chief coal mining countries including Poland, Czech Republic, the U.S., China, and Australia have experienced fatal accidents caused by coal burst and conducted comprehensive research on the driving forces and solving technologies related to coal burst. In this chapter, the research outcomes of the mechanism, risk evaluation, risk monitoring, and prevention of coal burst are reviewed, which is helpful for mining researchers and engineers to understand and control the safety hazards caused by coal burst, and, hence, to achieve sustainable and safe mining.

Keywords: coal burst, underground mining, mining safety, dynamic hazards, rock mechanics

1. Introduction

Coal burst, which refers to the violent and catastrophic failure of coal, is a serious safety hazard for underground coal mines, and it has attracted intensive research interests from mining and geological scholars [1]. In 1738, the first recorded coal burst took place in England [2, 3]. Since then, both the frequency and severity of coal burst increased with mining depth [2, 4, 5]. As shown in **Table 1**, coal burst has been a serious security issue that many countries face for decades. Coal burst has been recognized as a serious risk for Australia's underground coal mines following a fatal coal burst accident at the Austar Coal Mine [6, 7]. Because of lacking coal burst experience, it is difficult to find mature theories and technologies in Australian to explain, predict, monitor, or control coal burst. It is an urgent task to develop a coal burst risk assessment methodology and prevention technology for Australian coal mines. Extensive study has been conducted around the mechanism, prediction, and prevention of coal burst [5] by scholars around the world. Some necessary conditions of coal burst such as stiffness, dynamic load, and mechanical property are found based on previous decades' research.

In terms of energy, coal burst is the energy accumulation and releasing process of a coal body. Coal burst monitoring, such as acoustic emission, electromagnetic radiation, micro-seismic, infrared, and other methods, is the monitoring of different energy forms released during coal burst [8, 9]. The cause of the coal ejection and roadway destruction is the elastic energy stored in the coal [10]. Therefore,

Country/region	Time period	Number of coal bursts	Number of fatalities	Reference
Czech Republic/ Poland	1983–2003	190	122	
Ruhr, Germany	1973–1992	50	27	[4]
USA	1943–2003	–	78	
USA	1983–2013	337	20	[21]
Mainland China	1933–1996	4000	400	[5]
Mainland China	2006–2013	>35	>300	[36]

Table 1.
Coal burst occurrence and fatalities by country/region [7].

it is significant to have an understanding of energy release mode in the coal burst process, especially the magnitude of coal burst energy. Coal burst is regarded as a dynamic disaster since it is shown in many studies that coal burst is closely related to dynamic load [11]. It is believed that hard rock is more prone to violent failure than soft rock [12]. Due to the difference in physical and mechanical properties, different coal seams have a different coal burst propensity. Therefore, changing coal mechanical property is a promising method for coal burst mitigation. Water infusion can mitigate coal burst propensity through increasing moisture content of coal [13]. In this chapter, the coal burst driving forces, solving techniques, and monitoring methods are reviewed from energy aspects.

2. Potential driving factors

2.1 Mining depth

Mining depth has been identified as an important factor for the formation of coal burst. According to the analysis of coal burst cases in Poland and China, LM Dou found that the first coal burst accident in coal mines generally happened when mining depth approached 350 m and the frequency and severity of coal burst sharply increases with mining depth changing from 350 to 600 m [14]. Iannacchione and Zelanko found that nearly all coal bursts in the main coal fields of the U.S. occurred at depths greater than 300 meters, and most were at depths exceeding 400 m [15]. The contribution of mining depth to coal burst mainly results from the increasing gravitational stress. More strain energy will be stored in the coal under high gravitational stress condition [16]. Besides, for coal mines in China and the U.S., hard sandstone roof seems the common geological feature for deep mining, which can further result in a large accumulation of energy or a catastrophic dynamic load [17, 18]. The potential influence of hard roof (roof stiffness) also will be discussed in another section of this paper. The mining depths of two coal mines with coal burst accident in Australia are both around 500 m [19]. Hence, the strain energy accumulation led by high gravitational stress plays an important role in the formation of coal burst accidents that happened in Australia as the mining depth of these coal mines is already beyond the mining depth of majority of burst accidents revealed by international research.

More seriously, almost all coal mines in Australia have plans for deeper mining, which means the stress environments will be more complicated and more energy will be stored in coal seams [20].

2.2 Geological structures

It has been shown by numerous studies that the complicated geological structures caused by folds, faults, and coal seam thickness variation have a noticeable influence on the coal burst occurrence [21]. Dou et al. found that 72% coal burst accidents in Longfeng Colliery were related to faults [16]. The numerical study conducted by Chen et al. found that stress will concentrate near the coal face when the coal face approaches fault [22]. Mark found that coal burst accidents in the U.S. have a close relationship with faults [23]. Folds, which are created by compressional tectonic stress, may have high residual tectonic stress in the geological structures. Through the stress regression analysis of Huanghuiyan Colliery, Jiang et al. found that stress concentration tends to exit at the area near syncline axis [24]. The influence of geological structures on stress distribution is shown as **Figure 1**.

2.3 Surrounding rocks' stiffness

Stiffness of the surrounding rocks is one of the main factors giving rise to coal burst. Bieniawski found that rock samples are more prone to violent failure under the loading machine with high stiffness. The uniaxial compression tests of sample composed by coal and rock found that most elastic energy is stored in the coal part of the compound sample and the burst potential of the sample is positively related to the thickness of the rock part [25, 26]. Through theoretical analysis, Yang found that energy will flow from high stiffness material to low stiffness material [17]. Hence, the high stiffness of surrounding rocks will enhance the energy accumulation in coal seam. In addition, as shown in **Figure 2**, the strength of coal tends to have rapidly decreased under the high stiffness environment [27]. Generally, the high stiffness environment is related to the heavy and hard sandstone layer above the coal seam [28]. Sometimes, the thickness of sandstone layer can reach tens or even hundreds of meters [16].
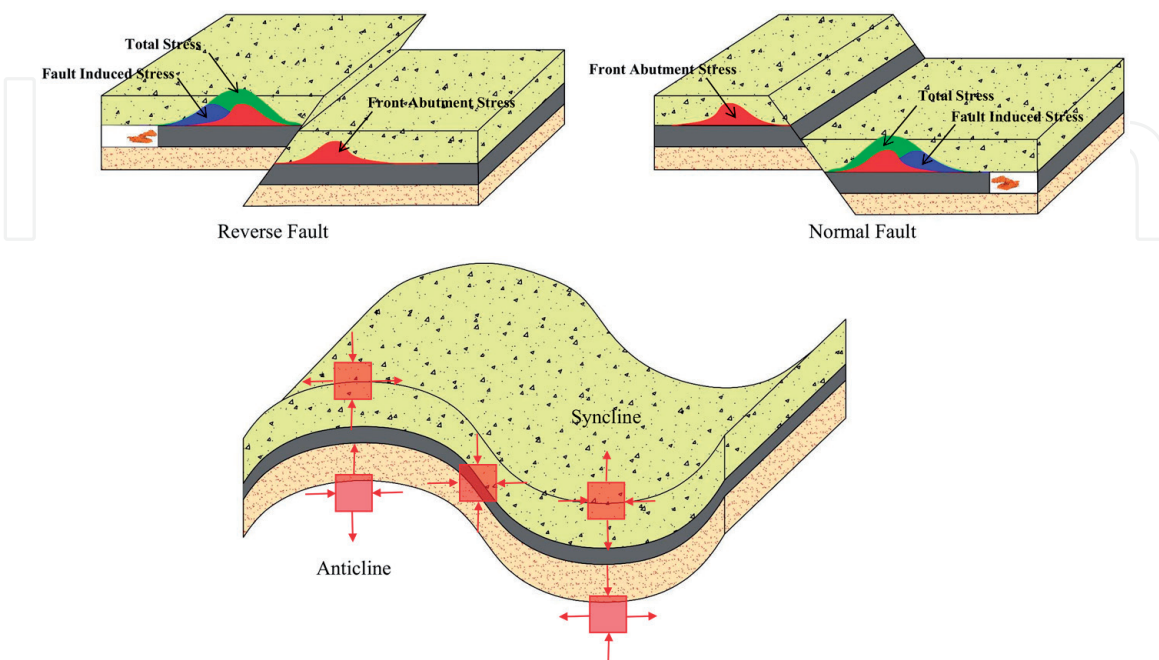

Figure 1.
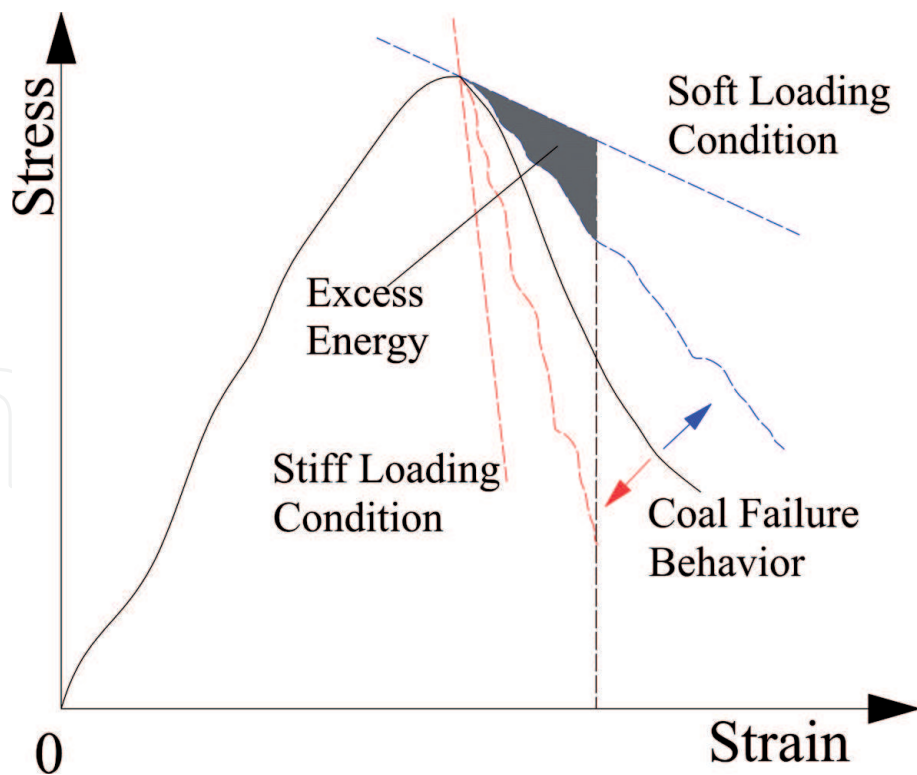*Stress concentration caused by geological structures.*

Figure 2.
Effect of stiffness of the loading system on the behavior of coal failure [17].

2.4 Micro-seismicity

Micro-seismicity refers to the regional small-scale seismic events that are undetectable by earthquake monitoring stations due to their small-scale energy compared with earthquakes. However, for underground coal mines, the energy released by micro-seismicity also is an important energy source for coal burst formation. Intensive micro-seismicity has been observed in most coal mines with high bursts risk in Poland, China, and the U.S. [29–31]. Micro-seismicity can be detected and located by specific micro-seismic monitoring apparatus. Deep research has been made by many researchers on the monitoring of dynamic load and identifying high burst potential areas through micro-seismic monitoring [32–34].

3. Previous mechanism

The study of the coal burst mechanism aims to explain the causes of coal burst from two perspectives: force source and coal's physical properties. As a type of coal failure, coal burst should meet the conditions of coal failure. That is, the stress loaded on coal exceeds the strength of coal when coal burst occurs, which is named strength theory by some scholars [16]. Satisfying strength theory is one of the conditions required by coal burst. Under static loading condition, coal burst does not always happen when the ultimate strength is reached. It has been pointed out that coal strength will change under dynamic load. Research has shown that the coal failure behavior is affected by loading rate as well [35]. In the actual situation, the strength theory of coal burst becomes more complex as the coal body is under the collective effect of static load (overburden weight) and dynamic load. Dou et al. [14] studied the dynamic load required by coal burst at different static load levels. Through a series of follow-up studies, LM Dou put forward the dynamic and static load superposition theory of coal burst [36, 37]. The strength theory of coal burst
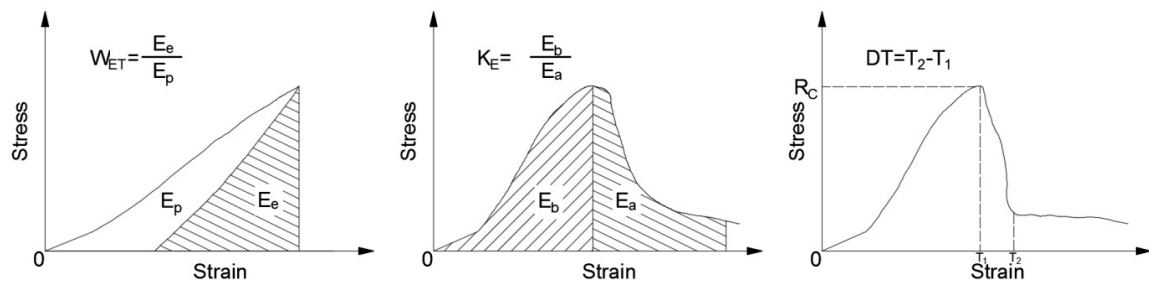
Figure 3.
Schematic diagram of coal burst propensity index [40]. (a) Determination of W_{ET} and (b) determination of K_E.

under dynamic load should be based on the dynamic strength of coal. Cook found that marble only has violent failure when the stiffness of the test machine is greater than the stiffness of the specimen [2, 16]. The compressive experiment of samples composed of coal and rock showed that violent failure always occurred in the layer with minimum stiffness [25, 38]. That is, the necessary condition for coal burst of a pillar or rib is that the stiffness of the roof and floor is greater than that of the coal seam. In most cases, the stiffness of coal seam is minimal relative to roof and floor. That is, coal failure in coal mines generally meet stiffness conditions.

It is found that the post-failure curve of hard rock is steeper than that of soft rock. This means that hard rock is more likely to fail instantaneously. Bieniawski et al. [39] believe that hard rock is much more prone to violent rupture than soft rock. It is necessary to explain that the hard rock and soft rock here are classified in terms of strength. Bieniawski proposed two indices, elastic strain energy index (W_{ET}) and bursting energy index (K_E), to measure the rock burst tendency of different rocks. As shown in **Figure 1**, elastic strain energy index is the ratio between elastic energy (E_e) and plastic energy (E_p) when the specimen is loaded to at least 80% of the strength and then unloaded [2]. K_E is the ratio between E_b and E_a [2]. E_b represents the energy storage before strength while E_a means deformation energy consumed after the peak value. It is proved by in suit and experimental data that coal with high W_{ET} and K_E value has a high tendency for violent failure [2, 4, 25]. These two indices describe the proportion of elastic energy during coal burst. Different rock types have different burst tendency and different energy storage and releasing behavior. Due to the difference in physical and mechanical properties, the W_{ET} and K_E values of different coal seams vary widely as well. Theoretically speaking, coal has no burst ability when the W_{ET} and K_E values are low enough. The ability or property of coal burst is called coal burst propensity by Chinese scholars. Four indices including W_{ET} and K_E are summarized as coal burst propensity indices by Chinese scholars and have become a good indicator of coal burst risk of different coal seams. Coal burst propensity index describes the proportions of different energies. The successful application of the coal burst propensity index method indicates that elastic energy and coal burst are closely related. Coal has the ability to store and instantly release elastic energy in the premise of coal burst (**Figure 3**).

4. Prevention methods

4.1 Evaluation

Based on the analysis of stress-strain curve of coal specimens under uniaxial compression stress, several special indices are published by different researchers to evaluate coal burst propensity. Russian and Poland coal mines adopt elastic strain energy index and bursting energy index to evaluate coal burst propensity [2, 4]. Zhang et al.

believe that the duration of failure process is the comprehensive reflection of energy accumulation and dissipation characteristics of coal [41]. They propose a dynamic failure time to evaluate coal burst propensity. Based on the correlation analysis of mass data, Qi et al. conclude that uniaxial compression strength of coal is a proper index of coal burst propensity evaluation as well [42]. In 2010, the China Coal Industry Association summarized these four indices as bursting liability indices of coal and published the standard test method of these four indices. Some researchers adopt these four indices to evaluate the burst propensity of rocks as well. It is has been proved by Russian, Poland, and Chinese experience that these four indices are good indicators to define the burst risk of coal seam. Besides, LM Dou et al. combined geological conditions and technical settings of mining together and proposed comprehensive index method based on the coal burst research in China [16].

4.2 Monitoring

Minimizing the safety risk caused by failure of instability rock/coal is an urgent and essential task for underground mines. Similar with the instantaneous failure of other brittle materials such as rock, concrete, and metal, the coal burst process is always associated with the release of rich geophysical signals including acoustic emission (AE) [43], micro-seismic [32] and electromagnetic radiation [44]. It is demonstrated by decades of research and in-field application that micro-seismic monitoring technology has a promising ability to locate potentially violent rock failure. Micro-seismic monitoring is a passive observation of very small-scale earthquakes that occur in the underground as a result of human activities such as mining, hydraulic fracturing, and underground gas storage. The phenomenon that stressed rock can release micro-level signal was discovered by two researchers of U.S. Bureau of Mines, Obert and Duvall, in 1938 [32, 34]. In the early 1960s, South African researchers developed a 16-channel micro-seismic system with positioning function for rock burst monitoring in gold mines [34]. In 1970, under the sponsorship of the U.S. Bureau of Mines, the Pennsylvania State Rock Mechanics Laboratory conducted a research project to investigate the application of micro-seismic techniques to coal mine safety [45]. Through decades' study of underground micro-seismic for mining operation, micro-seismic system has been a basic and valuable monitoring tool for metal and coal mines worldwide. It provides a continuous and real-time 4D (three dimension location and time) record of seismicity associated with rock failure in the monitoring region.

4.3 Controlling

The widely used coal burst controlling methods include provocative blasting, long-term water infusion, hydro-fracturing, de-stress drilling, and protective seam mining [46]. Dou et al. proposed the intensity weakening theory to guide the coal burst control from the aspect of energy [16]. Based on the energy aspects, the key to coal burst prevention are: (1) softening coal by changing the physical and mechanical properties of coal. The burst tendency or burst scale of soft coal will be mitigated as the energy storage ability of coal has been reduced. The main methods of coal body softening are blasting and water infusion. (2) Transferring stress to deep regions and reducing the stress level of coal, which can reduce energy storage as well. The main methods are pressure relief blasting, roof pre-splitting blasting, roof cutting blasting, protection seam mining, hydraulic roof fracturing, and large diameter pressure relief drilling. (3) Releasing energy by artificially induced coal burst under low stress level. The main methods are pressure relief blasting and large diameter pressure relief drilling.

Conflict of interest

The authors declare no conflict of interest.

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