# Investigation on the mechanism of coal mine bumps and relating microscopic experiments

# Y.X. Zhao & Y.D. Jiang

State Key Lab of Coal Resources and Safe Mining, China University of Mining and Technology, Beijing, P.R. China

ABSTRACT: This paper briefly describes the characteristics and induced factors of coal mining bumps based on the investigation of recent bump accidents that have occurred in China. According to the theory of non-equilibrium thermodynamics and dissipate structure, the process of strain energy accumulation and dissipation in the 'Coal-Surrounding Rock' system (CSRS) is discussed during the preparation of coal bumps. In addition, a series of experiments are conducted to analyze the relationship between bump-prone property and micro-structural characteristics of coal. The process of coal bumps induced by propagation of fractures and deterioration of coal mass properties are also analyzed systematically.

# 1 INTRODUCTION

Coal bump is defined as a sudden release of the geologic strain energy that can expel large amounts of coal and rock into the face area, resulting in fatalities and injuries to underground workers (Fig. 1). This has been recognized as a sudden catastrophic failure of coal and causes serious problems to underground coal mining worldwide in the past 100 years. In the past ten years, coal bump incidents have increased with rapid development of coal mining in China. Statistics showed that bump accidents caused hundreds of fatalities and injuries in the period from 1997 to 2008 in underground coal mines. Coal bumps have already been one of the most dangerous damage occurrences to underground mining safety in China. The other three destructive damage events are rock fall, coal and gas outburst and water inrush. So understanding the mechanism of coal bumps becomes more and more urgent.

In recent years, many attempts have been made to understand the mechanisms of coal bumps (Crouch & Fairhurst 1974, Burgert & Lippmann 1981, Salamon 1984, Babcock & Bickel 1984, Maleki et al. 1995) and methodologies were developed and proposed to predict the hazard based on seismic-acoustic or electromagnetic emissions (Fujii & Ishijima 1997, Arabasz et al. 1997, McGarr 1984). The investigations on the mechanism of coal bumps can be classified into three categories. First is theory analysis, which is composed of: (1) system modelling by elasticplastic theory (Lippman 1987,1990, Jiang 2005) and chaos and fractal theory (Xie 1993) to analyze the bump process; (2) the evaluation on the potential liability of coal bumps triggered by geological structures, progressive mining and blasting based on the theories of strain localization and coal petrology (Shepard 1981, Vardoulakis 1984, Jiang 2005); (3) the research on the features of accumulation and dissipation of strain energy by various indices (He 2007). Second is the experimental research work conducted in laboratories, which are mainly on the macroscopic mechanical properties (i.e. bursting liability indices of coal) and the structural features of the 'coal-surrounding rock' system (Kidybinski 1981, Babcock 1984, Cao 2001). Little attention has been paid to the microscopic features of bump-prone coal. The third part is numerical simulation. Various kinds of numerical modelling codes are developed or adopted to analyze the mechanisms of coal bumps according to data from geophysical and geomechanical surveys (Zubelewicz 1983, Baradet 1990, Cundall 1990, Muller 1991, Tang, 2005). The results of earlier investigations provided further knowledge of the processes that occur in a bump, and could help to improve our understanding of coal bump mechanisms.

The objective of this study is to analyze the features and the induced factors of coal bumps in China, and describe the preparation process of coal mine bump based on non-equilibrium thermodynamics and dissipate structure theory. In addition, two experiments were carried out to investigate the microscopic properties of bump-prone coal and the micro-process of unstable cracking in coal.



Figure 1. Characteristics of coal mining bumps. (a) Heavy equipment thrown by coal bump, Tangshan coal mine. (b) U-shaped steel support destroyed by bump, Laohutai coal mine.

# 2 FACTORS CONTRIBUTING TO COAL BUMPS

Statistics show that there are many factors contributing to coal bumps in China. One of the most significant factors is geological structures. It is observed that coal bumps occur in almost all kinds of coal seams except in brown coal collieries, based on the information from Chinese coal mines. They occur from 200 to 1100 m depth, with both simple to extremely complex geological structures, with both thin and extra thick coal seams, for horizontal to steep dipping seams, as well as for different types of surrounding rock. The other significant factor is the mining method. Coal bumps can be triggered by progressive mining in any mining situation. However, it has been proved that the frequency and magnitude of bumps are lowest at longwall faces and greatest in blast mining faces adjacent to coal pillars.

Though the factors contributing to coal bumps are shown to be significantly complex and diverse, they can be divided into two categories: prime factors and multivariable coupling factors.

## 2.1 Prime factors

Earlier investigations on coal bumps in China indicated that with increasing mining depth, the coal and surrounding rocks can store more strain energy, which always induce destructive bumps. The periodic failure of thick and stiff roofs may cause sudden release of strain energy to trigger bumps (Zhao 1991). The risk is raised with the deterioration of bump prone conditions. In other countries, many researchers have also identified prime individual factors contributing to coal bumps. Lippmann (1990) reported that translational bumps seem to occur only where the layered rock in the roof and floor are adjacent to the seam (due to stiffness contrasts), for example, where sandstone or hard shale are 10 times stiffer and stronger than the coal. Maleki (1998) have presented a survey of variables contributing to bump-prone conditions based on data from 25 cases involving U.S. coal mines. He identified roof beam thickness, local yield characteristics of the immediate roof/floor strata and stress gradients as being significant variables for triggering coal bumps. Thus the prime factors contributing to coal bumps can be concluded as mining depth, strong and stiff roof/floor, tectonic stress concentration, mechanical properties of coal, and geological structures.

# 2.2 Multivariable coupling factors

Though the prime factors play a more important role in triggering coal bumps, many bumps are induced by multivariable coupling factors. In view of assessing the influence of a combination of different factors, the information from four Chinese coal mines were studied, including the Zhao-gezhuang, Laohutai, Xinzhouyao and Yaoqiao mines. Figure 2 shows the locations of the studied mine sites. Table 1 presents the significant variables contributing to the coal bumps observed at these four mines. Figure 3 presents the effective weighting of the different factors on coal bumps. The results indicate that the important variables should include the effects of bump liable coal, mining depth, geological structures, coal pillar as well as earthquakes or blasting tremors. So the multivariable coupling factors can be defined as:

Energy release ratio - includes the effects of depth, coal properties, and geological structures.

Disturbed ratio - includes the effects of mining method, and blasting or earthquakes tremors.

*Coal Pillar stability index* - includes geometry of the coal pillars, and the surrounding rocks conditions.



Figure 2. Locations of mine sites in the study.



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Collieries							
subject to	Bump places	Variables affected coal bumps					
coal bumps							
Zhaogez-	Adjacent to 2337#	bump liabili-	Mining	Tectonic	Blast mining	Geological	Earth-
huang	working face	ty coal	depth	stress	method	structure	quakes
Laohutai	At gate road of 83001# working face	bump liabili- ty coal	Mining depth	Strong and stiff roof	l Coal pillar	Geological structure	Blast tunneling
Yaoqiao	Air return dip in central panel	bump liabili- ty coal	Mining depth	Strong and stiff roof	l Coal pillar	Geological structure	
Xinzhouyac	Adjacent to 8727# working face	bump liabili- ty coal	Dis- turbed ground	Strong and stiff roof	l Coal pillar		

Table 1. Statistical summary of the variables contributing to different coal bumps.

# 3 THERMODYNAMIC ANALYSIS OF COAL BUMPS

The complexity of coal bumps is controlled by the complexity of the 'Coal-Surrounding Rock' system (CSRS), the uncertainty of microstructures in the coal, the diversity of the factors contributing to coal bumps, and the coupling effects of various thermo-mechanical processes in the coal seam with progressive mining. It is very difficult to express exactly the preparation process and mechanism of coal bumps with traditional methods. Earlier research indicated that coal bumps can be characterized as an unstable release of energy in time and non-uniform in space, which was associated with yielding during progressive mining. At that time, the failure of 'Coal-Surrounding Rock' system would be unstable. The velocity of energy release in the system should be larger than the velocity of energy dissipation. And the various energy release gradients on different points formed the non-uniform energy dissipation in space, which can cause the instability of the system.

The CSRS was a compressive system and the strain energy in the system was consumed and dissipated during stages of cracks initiation, growth and coalescence in the coal. With increasing energy dissipation, the free energy in the system increased and the total potential energy decreased. The stability of the system progressed to a more stable stage through regular cracking in the coal. However, the releasing of free energy was easily affected by the ambient mining conditions. For example, slip along a fault, roof failure and fall, blasting, etc., could each induce a violent failure of the system adjacent to the excavation and even trigger coal bumps. Figure 4 illustrates the process of the system from its original stable state to a new stable state triggered by free energy release.



Figure 4. Different stages of free energy stored in the 'coal-surrounding rock' system.

However, the forming of coal bumps is mainly associated with underground mining operations. The progressive mining is a dynamic and irreversible process. With time, continual deformation and failure occurs in the rock and coal adjacent to the excavation surfaces causing the release and transformation of accumulated strain energy in the surrounding rock, which can also cause the system to evolve into a dissipation structure. From a micromechanical point, the effect of strain energy accumulation changes the quantity, state and distribution of defects in the coal seam and/or surrounding rock. The microstructure is self-organized and changes during this process, which can eventually direct the system towards a stable direction. From a macroscopic point of view, the concentration of strain energy can induce a mutation of the stability of the 'coal-surrounding rocks' system. Based on thermodynamic theory, the natural features of the physical process in any material are the transformation and transition of energy, but the failure process is an unstable phenomenon driven by the energy dissipation. The energy dissipation is the result of an irreversible thermodynamic phenomenon. Therefore, the energy dissipation can be used as a bridge to connect the microscopic and macroscopic mechanisms of coal mine bumps. Accordingly, it is very useful to understand the mechanisms of coal bumps by studying the regularities of energy accumulation, transformation and dissipation in coal bumps from preparation to occurrence; analysis on the effect of physic-mechanical parameters to coal bump is also efficient and necessary.

According to the theory of non-equilibrium thermodynamics and dissipation structure, the assumption can be proposed that the CSRS is a closed system prior to the coal seam being excavated. During excavation, the internal energy of the coal unit depends on the variation of internal stress and the flow of heat, which can cause an unbalanced state of energy in the CSRS. Thus the internal energy balance becomes a dynamic process. The energy conservation equation for a coal volume element is:

$$\rho \frac{d\tilde{e}}{dt} = -\nabla \bullet \tilde{j}_q + 3\sigma_m \dot{\varepsilon}_m + \mathbf{S} : \dot{\vec{\varepsilon}} + \mathbf{S} : \dot{\vec{\omega}} + \sum_i \tilde{j}_i^m \bullet \vec{F}_i$$
(1)

Where  $\rho$  is the density of coal volume element,  $\tilde{e}$  is the intrinsic energy of unit weight coal,  $\bar{j}_q$  is the heat flow through the volume element of coal,  $\bar{j}_i^m$  means the divergent flow of mass, and  $\bar{F}_i$  is the body force on some component.  $\bar{P}$  is the external force applied on the surface of volume element and **S** is the deviatoric stress tensor. The entropy source intensity is:

$$\zeta = \vec{j}_q \bullet \nabla \left(\frac{1}{T}\right) + \frac{\mathbf{S}}{T} : \dot{\vec{\varepsilon}} + \frac{\mathbf{S}}{T} : \dot{\vec{\omega}} - \frac{R_{\infty} \left(1 - e^{-b\varepsilon^p}\right)}{T} \dot{\varepsilon}^p - \frac{2X_{\infty} \gamma \alpha_{ij}}{3T} \dot{\alpha}_{ij} - \frac{n\varepsilon^{n+1}}{2\varepsilon \varepsilon_s^n D^2} \dot{\varepsilon} - \frac{A_r}{T} \omega_r \tag{2}$$

Based on the non-equilibrium thermodynamic assumptions, the thermodynamic process is linear and satisfied with minimum entropy principle. If  $d\zeta/dt < 0$ , the system will be unstable. The process should obey the following equation:

$$\vec{j}_{q} \bullet \nabla \left(\frac{1}{T}\right) + \frac{\mathbf{S}}{T} : \dot{\vec{\varepsilon}} + \frac{\mathbf{S}}{T} : \dot{\vec{\omega}} \ge \frac{R_{\infty} \left(1 - e^{-b\varepsilon^{p}}\right)}{T} \dot{\varepsilon}^{p} + \frac{2X_{\infty} \gamma \alpha_{ij}}{3T} \dot{\alpha}_{ij} + \frac{n\varepsilon^{n+1}}{2E\varepsilon_{s}^{n}D^{2}} \dot{\varepsilon} + \frac{A_{r}}{T} \omega_{r}$$
(3)

In addition, based on basic thermodynamics theory, we can assume the thermodynamic process in the system is in the linear region of a non-equilibrium state at the beginning of mining. Thus, only if the strength of entropy production in the volume element is less than 0, the system will deviate from equilibrium and a stationary state, therefore potentially causing an unstable failure of the CSRS. However, with increasing influence by mining or tunneling, the thermodynamic process adjacent to the roadway becomes nonlinear. According to the local thermodynamic equilibrium assumption and stability theory of non-equilibrium nonlinear stationary state, the excess entropy production can be adopted to evaluate the process stability in the coal seam near the excavations. The thermodynamic process should be satisfied with the equation:  $\delta^2 \zeta < 0$ . Furthermore, the system is progressively stable if  $d(\delta^2 \zeta)/dt > 0$ , it is at the threshold point as  $d(\delta^2 \zeta)/dt=0$ , and if  $d(\delta^2 \zeta)/dt < 0$ , the system will be unstable.

In summation, the region far from the coal seam excavation was stable and saw little effect from the mining during the roadway tunneling process. The stability of the coal mass adjacent to the excavations can be determined by the stability of internal thermodynamic process. The factors which affect the thermodynamic process in coal are mainly stress gradient, plastic transformation, microstructures and macerals in the coal.

# 4 EXPERIMENTS ON THE MICROSCOPIC PROPERTIES OF BUMP PRONE COAL

Thermodynamic analysis indicates that the microscopic properties and the micro-cracking features of coal affect the bump prone conditions significantly. Two experiments were conducted to analyze the relationship between bump-prone properties and micro-structural characteristics of coal. In addition, the process of coal bumps induced by propagation of fractures was also analyzed systematically.

# 4.1 Microcracking features in bump prone coal

Three Point loading tests with Scanning Electron Microscopy (SEM) observations were performed on three samples from No.12 coal seam in Zhaogezhuang mine (Samples: ZGZ-TPL1, ZGZ-TPL2 and ZGZ-TPL3) and three samples from 8727# working face, No.11 coal seam in Xinzhouyao mine (Samples: XZY-TPL1, XZY-TPL2, XZY-TPL3). A bump occurred at 8727# working face several weeks after sampling. Fortunately there was nobody working there at the time and samples influenced by the bump could be collected (Samples:XZYCH-TPL4 and XZYCH-TPL5). Figure 5 presents the load-stoke curves of three samples. The test results show that the samples not influenced by the bump are characterized as brittle with sudden failure, and those influenced by the bump can be characterized as viscous ductile failures. The strength of the bump-influenced coal is notably decreased compared to the coal not influenced by the bump (see Fig. 5b and c). Thus it was proved that the thermodynamic process of a coal bump does influence the internal micro-structures of coal. According to the information from the bump sites studied and the theories of coal petrology, coal bumps are always accompanied by rapid increasing of temperature in the surrounding coal. The generated heat and rapid release of strain energy can increase the amount of damage and microcracks, changing the coal's physical-chemical properties.



Figure 5. Comparison of load and displacement curves in the three bending tests for specimens: (a) ZGZ-TPL2, from No.12 coal seam in Zhaogezhuang mine; (b) XZY-TPL1, from No.12 coal seam in Xinzhouyao mine; and (c) XZYCH-TPL4, influenced by a bump, from No.12 coal seam in Xinzhouyao mine.



Figure 6. Crack propagation characteristics in the specimen of XZYCH-TPL4 with increasing load. Several significant decreasing stages of load are shown in the load-stoke curves. The results indicate that a sudden propagation of micro-cracks and unstable cracking features in the coal specimen. The following features best explain the thinning out, propagation, influx and coalescence of cracks in the specimen:

(1) Microcracking initiated as the load increased to 20~30% of the peak load. The initiation of cracks was generally adjacent to the primary defects where stresses concentrated or the weak zone connecting different macerals (see Fig. 6a).

(2) The initiation and thinning out of cracks depend mainly on the variation of stress gradients. The direction of crack tip propagation and propagation velocity were determined by the magnitude of stress and micro-structure distribution in the specimen, as shown in Figure 6b.

(3) The nonlinear features such as bifurcation and chaos were found in the process of influx and coalescence of crack sets in the bump prone coal. Figures 6c and d present the mutual inhibition and competition of different crack sets in the failure process. It was revealed that the coalescence and propagation of a main crack can induce closure of other secondary cracks. In addition, the path of micro-cracking was concentrated in the stratification planes of specimen or the macerals with relatively small micro-hardness. The fractal characteristics were revealed in the geometrical features of the cracking path.

(4) Based on the analysis of micro-cracking features in the bump prone coal, the Least Energy Consumption Principle can be adopted to describe the micro-process in the preparation of coal bumps. Figure 4 also illustrates the failure process of the CSRS induced by unstable fracturing in coal.

### 4.2 Maceral analysis on the bump prone coal

Thermodynamic processes through the mining conditions were influenced by not only the unstable propagation of cracks, but also the macerals in the coal. So a bump liability indice  $\zeta$  was proposed based on the analysis of the micromechanical properties of bump prone coal. The samples were from the No.7, 9 and 12 coal seams in Zhaogezhuang mine, and No.11 coal seam in Xinzhouyao mine. Table 2 illustrates the sampling features and locations. X-Ray Diffraction (XRD) was applied to achieve the diffraction pattern and XRD parameters of different coal samples. A comparative analysis was carried out on the bump-influenced coal and original coal. In addition, the macerals and the vitrinites reflectance in different samples were studied to analyze their influences to the properties of bump prone coal.

Sample Num	Sampling place	Depth/m	Description*
ZGZ-M1	West 1# crosscut in 13 panel, No.9 coal seam, Zhaogezhuang	-1100	Coal and gas outburst prone seam
ZGZ-M2	West 1# crosscut in 13 panel, No7 coal seam, Zhaogezhuang	-1100	No outburst and bump liability seam
ZGZ-M3	East 4# crosscut in 12 panel, No12 coal seam, Zhaogezhuang	-1000	Extremely bump liability seam
XZYCQ1	8727# working face, No.11 coal seam,Xizhouyao (before a bump)	-300	Moderate bump liability seam
XZYCH1	8727# working face, No.11 coal seam, Xizhouyao (after a bump)	-300	Moderate bump liability seam

Table 2. Sampling positions and features description.

\* The bursting liability of different coal seams were determined by failure duration index, energy index and bursting energy index (Zhao 2006).

Based on petrology, the microstructure features of the coal were defined using three parameters:  $d_{002}$ , the interlamellar spacing of aromatic layer;  $L_c$ , the average packing thickness of microcrystalline laminas; and  $L_a$ , the diameter of aromatic layer. These three parameters can be calculated usin the following formula:

Where  $\lambda$  is the wave length of the X ray,  $\theta_{002}$  and  $\theta_{100}$  are the peak positions of 002 and 100 peaks respectively (in degrees), and  $\beta_{100}$ ,  $\beta_{002}$  are the full width at half maximum of 002 and 100 peaks (in radians).

From these, the bump liability indices  $\xi = (L_a - L_c)/L_c$  can be proposed to determine the bump potential of coal. It was found that the bigger the  $\xi$  value, the more dangerous and liable to a bump the coal seam would be.

Test results showed that the  $\xi$  values of ZGZ-M1, ZGZ-M2, ZGZ-M3, XZYCQ1 and XZYCH1, were equal to 0.135, 0.154, 0.162, 0.930, and 0427, respectively, which indicated that coal bumps can be triggered more easily in the No.11 coal seam in Xinzhouyao mine compared with the three coal seams in the Zhaogezhuang mine, even under the same geological and mining conditions. The results also indicate that the critical depth for bump occurrence at the Xinzhouyao mine is just 300m, but ranges up to 860 m at the Zhaogezhuang mine. It was also proved that energy dissipation through the bump preparation process affects the mechanical properties of coal, with a decreasing  $\xi$  value in the bump-influenced coal. Table 3 presents the maceral amounts in the different samples. The results indicate that the samples composed of more vitrinites and inertinites have more potential to bump. Table 4 presents the vitrinites reflectance of different samples, which indicate that the maximum vitrinites reflectance  $(R_{max})$  and minimum vitrinites reflectance  $(R_{\min})$  are not sensitive to the bump prone indices separately. But the value of  $|R_{\text{max}}-R_{\text{min}}|$  can be used to assess the bump liability: the smaller the value of  $|R_{\text{max}}-R_{\text{min}}|$  $R_{\min}$ , the less potential for coal bumps. The results also indicated that the microstructure features can aid to determine the bump liability and the historical stratigraphic evolution can be recorded by the microstructures in coal.

	Sample Number	ZGZ-M1	ZGZ-M2	ZGZ-M3	XZYCQ1
Vitrinite	Desmocollinites	7.6	10.6	3.0	19.5
	Homocollinite	49.3	4.8	45.3	11.0
	Telinite	15.7	32.2	20.9	41.2
	Corpocollinite	4.7	7.4	2.6	3.7
	Vitrodetrinit	1.2	0.4		
	Semifusinite	2.9	10.2	11.5	10.2
	Fusinite	4.9	9.2	9.3	5.3
Inortinito	Detritus	2.5	16.6	4.8	4.3
mertime	Macrinite		0.4		0.2
	Micrinite		0.6		
	Sclerotinite		0.6		
Exinite	Sporophyte		0.6		1.8
	Cutinite				
	Resinite				
	Clay mineral	2.4	5.8	0.2	2.2
Minerals	Pyrite			2.2	0.2
	Carbonatite	8.8	0.6	0.2	0.4
	Others				

Table 3. Statistics of macerals observed in the different coal samples.

Sample Number	<i>R</i> <sub>min</sub> /%	$R_{\rm max}$ /%	$R_{ m o,max}$ /%	$ R_{\rm max} - R_{\rm min} /\%$	Observation point num
ZGZ-M1	1.10	1.17	1.14	0.15	20
ZGZ-M1	1.11	1.21	1.16	0.08	20
ZGZ-M1	1.19	1.24	1.22	0.18	20
XZYCQ1	0.76	0.85	0.81	0.15	20

Table 4. Reflectance ratio of vitrinites in different samples.

\*  $R_{\text{max}}$  is the maximum vitrinites reflectance,  $R_{\text{min}}$  is the minimum vitrinites reflectance, and  $R_{\text{o,max}}$  is the average vitrinites reflectance.

#### **5** CONCLUSIONS

Coal bumps can be characterized as the process of unstable energy release with time and nonuniform in space, which is associated with yielding that occurs with progressive mining. Many variables can affect the bump prone conditions. This paper briefly described the characteristics and induced factors of coal mining bumps based on the investigation of recent bump accidents that occurred in China and investigated the thermodynamic process in the nucleation of coal bumps. The following conclusions have been drawn regarding the micro-structural features of bump prone coal and their potential application to better understanding coal bump mechanisms:

(1) The far-field region away from excavations in the coal seam was stable and saw little effect from the mining during the roadway tunneling process. The stability of the coal mass adjacent to the excavations can be determined by the stability of internal thermodynamic process. The factors which affect the thermodynamic process in coal are mainly stress gradient, plastic transformation, microstructures and macerals in the coal.

(2) A bump liability indices  $\xi = (L_a - L_c)/L_c$  was proposed to determine the bump potential of coal. It was found that the bigger the  $\zeta$  value, the more dangerous and liable to bump in the coal seam. The macerals analysis revealed that the coal, composed of more vitrinites and inertinites, had more potential to bump because of the micro-hardness and micro-brittleness. The value of  $|R_{\text{max}}-R_{\text{min}}|$  had some relationship with bump liability: the smaller the value of  $|R_{\text{max}}-R_{\text{min}}|$ , the less potential of coal bumps. The results also indicated that the microstructure features can aid to determine the bump liability and the historical stratigraphic evolution, which can be recorded by the microstructures in the coal.

(3) It was also proved that energy dissipation in bump preparation process affects the mechanical properties of coal significantly. The influence on bump liability can be described quantitatively by the  $\xi$  value.

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