Chapter 3
Mechanism and Predicting Theory-Based of Rockburst Evolution

3.1 Introduction

The dynamic hazard, caused by failure of surrounding rockmass because of rock excavation, is the most direct danger of mining safety and efficient production. Many scholars (Wang et al. 2014, 2015; Lindin and Lobanova 2013; Chen et al. 2015; He et al. 2010; Pan et al. 2014) paid much attention to it. Although many achievements were be made in theoretical and field cases, there is no unified understanding of rock dynamic hazards, especially the mechanism and predicting of rockburst, and further research is needed. Previous researches on rock failure and rockburst induced conditions have been carried out, but the mechanism and predicting of rockburst is complicated, and there is no mechanism and prediction model to explain the occurrence of rockburst satisfactorily. Therefore, the study of predicting rockburst induced conditions and the failure behavior of rock fracture is analyzed by proper theory. Most of these can provide reasonable suggestions for mining design; mining method selection and rockburst hazard prevention measures. It is of great significance for mine safety and high efficiency mining. In complex mining conditions, in order to solve the key technical problems of predicting rockburst, first of all, it is necessary to analyze the conditions induced rockburst, so as to lay the foundation for predicting of rockburst. The essence of rock failure is the release of elastic strain energy stored in rock under the action of stress. Therefore, one of key factors to study rock failure is the stress distribution in rock and the relation between rock elastic energy and dissipation energy per unit volume. If most of energy absorbed by rock is dissipated during loading, then the final failure mode of rock will be static. On the contrary, it is dynamic.

On the basis of these, combined with the deformation characteristics of rocks, the author explored the stress-energy mechanism of rockburst. Since the 1970s, the emergence of nonlinear theory greatly promoted the development of rock mechanics such as mutation theory, dissipative structure theory, fractal structure theory etc. Using these theories to study rock failure and rockburst, it not only

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correctly described its nonlinear dynamic characteristics, but also developed new concepts, new theories and methods for predicting rockburst.

In this chapter, the rockburst induced mechanism, rockburst predicting dynamic theory and rockburst stress-energy process were introduced in detail, and new predicting models and methods were established based on these theories. Experimental and field investigations showed that the application of these methods achieved the desired results, but also provided a new method for rockburst predicting.

3.2 Mechanism of Rockburst

Rockburst is generally considered to be induced by mining and accompanied by microseismic activity and elastic energy release. The excavation will disturb the original rock stress field. When the stress redistribution causes the surrounding rockmass to reach the critical state of destruction, some external factors, such as blasting stress wave and so on, may cause severe damage to the surrounding rockmass. In mechanism, rockburst is characterized by its occurrence and dynamic process compared with statics. But compared with dynamics, the evolution process of rockburst is quasi-static. It is a mechanical process from static deformation to loss of stability, and a result that rockmass structure loses its bearing capacity gradually and its stability finally. Therefore, the sufficient elastic strain energy and the stress concentration place are two main conditions to induce rockburst.

The released elastic strain energy stores in rockmass is the evolution process of rockburst. The key of rock failure is the internal stress distribution and the unit volume of rock elastic energy dissipation, and most of energy absorbed by rock is dissipated during loading, then the final failure mode of rock will be dominated by static. On the other hand, if the energy dissipation is less during the loading, rock will destroy more strong eventually, and some elastic energy will also be converted into the kinetic energy. Cook (1966) proposed the energy theory of rockburst in 1960s. It was pointed out that rockburst occurs when the mechanical equilibrium state of surrounding rockmass system was destroyed, and the energy released was greater than the energy consumed. In the 1970s, Brauner (1994) proposed the energy rate theory:

$$\alpha\left(\frac{\mathrm{d}E_R}{\mathrm{d}t}\right)+\beta\left(\frac{\mathrm{d}E_E}{\mathrm{d}t}\right)>\frac{\mathrm{d}E_D}{\mathrm{d}t} \tag{3.1}$$

α is effective coefficient of surrounding rockmass energy release, β is effective coefficient of energy release of orebody, E_R is the energy stored by surrounding rockmass, E_E is energy stored by orebodies, E_D is energy consumed at the junction of orebodies and surrounding rockmasses. Energy theory, based on the law of conservation of energy, breaks the limitations of traditional theory and answers the question of energy source of rockburst.

From the point of stress concentration, the main idea is that once the stress on rock exceeds its limit of strength, rock begins to break. The early researchs took the surrounding rockmass system as the object, and considered that the key to rockburst was the strength of surrounding rockmass system. Later, people gradually realized that the decisive factors that lead to rockburst are not only related to the strength of surrounding rockmass system, but also to the stress environment, mineral composition and excavation activities of rockmass. Under uniaxial loading, one of necessary conditions for rockburst is that the stress is greater than the compressive strength of rock. Under the triaxial loading condition, when the stress in the two directions is constant, the load in the third directions is gradually reduced. The stress value of rockburst was lower than that of rock (He et al. 2010). Therefore, according to the stress condition of rockburst, the method of reducing stress concentration is often adopted to prevent rockburst. If there is no necessary control for the surrounding rockmass, the elastic strain energy of surrounding rockmass storage will be converted to the kinetic energy of broken rockmass, which may lead to rockburst.

3.3 Mechanism of Rockburst Stress-Energy Evolution

Rockburst is a nonlinear dynamic process. In the course of its occurrence, part of energy is transformed into kinetic energy of broken rock blocks, and the broken rock blocks are ejected. Therefore, from the energy point of view, rock in compression deformation stage must accumulate enough elastic strain energy, in order to ensure more energy transfer to the kinetic energy of rock failure. The energy condition of rockburst is that the elastic strain energy accumulated in the process of rock compression is much larger than the energy consumed.

Rockburst is essentially a rapid release process of elastic strain energy accumulated in the rockmass. The main factors that affect the occurrence of rockburst is actually the impact of rockmass into a high energy storage factor, high energy rockmass are more likely to rockburst, and become high energy rockmass includes two aspects, that is to say, rockmass had sufficient capacity to store large elastic strain energy and a high concentration of stress (Zhao 2015). The conditions for the occurrence of rockburst propagation are as follows: a high concentration stress status and a large amount of releasable strain energy. Based on these two conditions, the mechanism of stress-energy evolution in rock is discussed.

Because of initial damage of rockmass, the density changes for this reason. Thus, the expansion of microhole and microcrack, which are caused by loading, are called positive damage. Similarly, the closure of microcracks and micropores is called negative damage. According to the basic principle of damage mechanics and rock mechanics, the pre-peak stage of uniaxial static loading of rock is regarded as the stage of rockburst evolution. From the energy point of view, the energy evolution of

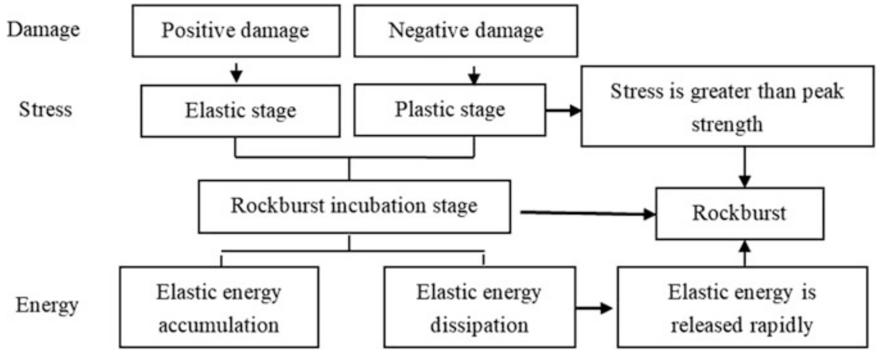

Fig. 3.1 The diagram of stress-energy mechanism of rockburst preparation and development

rockburst is mainly divided into two stages: energy accumulation and energy dissipation. The occurrence of rockburst is energy release. From the stress point of view, rockburst occurs at the pre-peak stage, while rockburst occurs at the post peak stage, as shown in Fig. 3.1.

In the initial stage of rock deformation, rock stress is small, the stress distribution is relatively uniform, the micro-cracks are compacted, the rock structure units are in the elastic stage, the elastic strain can begin to accumulate and rockburst is at the incubation stage. In addition, due to the micro-crack closure, the macro damage variable becomes smaller, negative damage occurs, rock mechanical properties are strengthened, the elastic modulus becomes larger, and the energy storage capacity of rock is improved.

Rock has passed an initial stage of compressive deformation and enters elastic stage. With the increase of stress, most of structural units are still in a stable status, and the elastic strain can begin to accumulate in large quantities, which is the key stage of rockburst evolution. This moment the microcracks are basically compacted and the damage cracking is not obvious. However, in the middle and late stages of the elastic stage, due to the increase of stress and the material properties lead to stress concentration part of structural unit, rock stress exceeds its compressive strength. The structural units lose its load-bearing capacity, and then the macroscopic damage of rock changes from negative damage to positive damage and the elastic modulus starts to decrease and the elastic strain energy begins to dissipate.

As the load continues to increase, rockmass enters the plastic deformation stage. As a result of material composition and structure of rockmass, the plastic phase of rockmass generally is relatively short, and some rocks even destroy directly during the elastic stage. In the plastic stage, a large number of rock units are destroyed because of increase of stress. The damage cracking is aggravated, the microcracks are expanded rapidly, and the macro fracture cracks are formed. The strain energy dissipation is increased, and the damage variable increases rapidly. At this point, rock is in the critical state of rockburst occured. When rock failure criterion is reached and sufficient strain energy is released, rockburst may occur at any moment.

In this chapter, the mechanism of rockburst stress-energy evolution is obtained by analyzing the pre-peak stage of rock compressive deformation: rockburst, as a way of rock fracture, is mainly caused by the accumulation of stress and the accumulation release of elastic strain. The change of stress for rockburst occurred plays a leading role, not only it leads to the accumulation and release of elastic strain energy, but also the damage cracking unit of rock structure. Thereby, reducing the energy storage capacity of rock elastic strain energy. In addition, the elastic strain energy released by rockburst is the result of accumulation and dissipation of elastic strain energy.

3.4 Nonlinear Dynamic Theory of Predicting Rockburst

3.4.1 Mutation Theory

The stable and unstable statuses referred to the theory of mutation are relative to certain control conditions. Under the control of external forces, the stable and unstable status of system can be freely transformed. If the initial state of system is stable, the status of system will change as a result of continuous control force. When the control factor reaches a certain limit (critical value), the status of system has reached the critical status of stability and instability. Although the control factor no longer changes, the status of system remains rapidly away from the critical value, changing to another stable state rapidly and this is the mutation. When the control factor reaches the critical value, the mutation does not occur. However, the mutation was occured within a certain period of time after the critical value (Shen 2006). When the specimens are subjected to external loads, the internal microcracks continue to develop, expand, merge and coalescence and the damage keep accumulating. When the internal damage accumulates to a certain extent, rock are in the critical state and the system tends to be unstable, a little disturbance of stress will lead to a sudden change of rock status. The macroscopic behavior is sudden failure of rock. Mutation theory, which is a nonlinear theory that studies the phenomenon of sudden change, can solve such problems very well.

Through AE testing of specimen loading, the damage was described using the mutation theory; the characteristics during the evolution of rock damage were obtained. In this chapter, the cumulative damage instability and the precursory characteristics of rock failure were analyzed.

3.4.2 Damage Theory

Damage theory is a new branch of mechanics developed around 1970s. Kachanov (1958) studied the creep failure of metals, the concept of continuity factor and effective stress were proposed to study the influence of internal defects on the deformation and failure of metals. Later, Robotnov (1969) introduced the concept of damage factor, and they did pioneering work for the establishment and development of damage mechanics. Lemaitre (1974) applied the concept of damage to low cycle fatigue. In 1974, British scholar Leckie (1974) and Swedish scholar Hult (1975) promoted the development of damage theory in the study of creep. Using the theory of continuum mechanics, many scholars were regard damage factor (DF) as a field variable and called it a damage variable. Thus, the basic frame and foundation of damage mechanics were formed.

Damage mechanics can establish damage evolution equation by defining specific damage variables. Therefore, the effects of damage on rock deformation characteristics can be reflected, especially for nonlinear dynamic processes such as rockburst. The damage theory was used to describe the physical processes of rockbursts (Sato et al. 1986). Under the action of external force disturbance, tensile stress status of local damage appeared in the rockmass (Leighton 1982). When the stress exceeds certain ultimate strength, new microcracks were formed in the rockmass. With the increase of external force, a large number of microcracks were gathered in some weak areas of rockmass, which was called the serious damage zone (Ma et al. 2016). In the evolution of rockburst damage, many scholars established a variety of macroscopic damage models.

In the process of loading, AE events were closely related to the interaction and propagation process of microcracks. Therefore, AE events were consistent with the damage of specimen. The pattern of rock failure change was analyzed, and the damage evolution model was established using damage mechanics theory based on AE parameters.

3.4.3 Load/Unload Response Ratio Theory

Load/unload Response Ratio (LURR) theory can be defined as the specific value between the loading response and unloading response. LURR can be used to quantify the status and degree of failure of a nonlinear system. Therefore, it can be used to predict rockburst. A schematic diagram is shown in Fig. 3.2, where the horizontal axis represents the responsive displacement (S) and the vertical axis represents the load (F).

Two parameters are defined to quantitatively distinguish the difference between the load/unload responses:

The response rate X is defined as

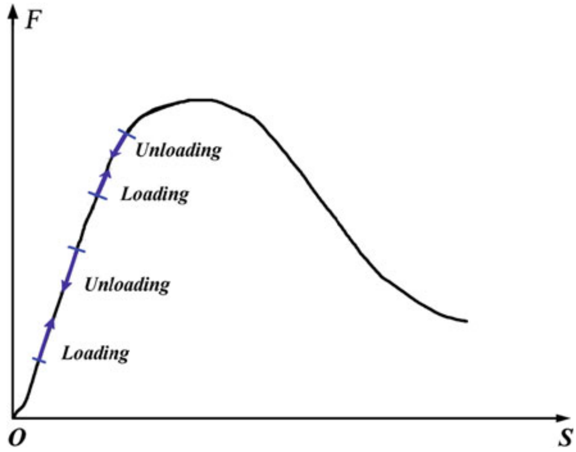

Fig. 3.2 Uniaxial load/unload schematic diagram

$$X = \lim_{\Delta F \to 0} (\Delta S / \Delta F) \tag{3.1}$$

where ΔF and ΔS are the increments of load F and the responsive increments of displacement S, respectively.

LURR Y is defined as

$$Y = X_+ / X_- \tag{3.2}$$

where X_+ and $X\_$ are the response rates for the load/unload conditions, respectively. Then,

$$\Delta F / \Delta S = k \cdot \mathrm{d}\sigma / \mathrm{d}\varepsilon = k \cdot E_d \tag{3.3}$$

where E_d is deformation modulus in MPa and k is a constant, which is defined as

$$k = A / l \tag{3.4}$$

where A is the cross-sectional area of cylindrical specimen (m^2) and l is the length of rock specimen (m). Therefore, the response rate X is inversely proportional to the deformation modulus.

As shown in Fig. 3.1 and Eqs. (3.1)–(3.3), during the elastic deformation stage, the loading path is reversible, meaning that the load/unload moduli are equal. Therefore, during this stage, the loading response rate of rock specimens is equal to the unloading rate, or $X_+ = X_-$. Based on Eq. (3.2), the Y value (LURR) is equal to 1, meaning that the deformation of rock specimens can be restored. During the plastic deformation stage, the loading response rate of rock specimens is greater than the unloading rate ($X_+ > X\_$). The Y value (LURR) is greater than 1, meaning that the physico-mechanical properties of rock specimens are reduced, such as deformation modulus, void ratio and compressive strength. As a result, LURR theory can be used to predict the degree of failure in the rock specimens.

Based on AE energy and Y value (LURR) theory, AE energy is proposed as a response rate (X) in Eq. (3.1). Then, the Y value of load/unload energy response ratio (LUERR) can be defined as

$$Y = \left[\sum_{i=1}^{N+} E_i^m\right]_+ \Bigg/ \left[\sum_{i=1}^{N-} E_i^m\right]_- \quad (3.5)$$

where E is AE energy released in these experiments from the rock specimens, the sign '+' refers to loading, '−' refers to unloading, and m = 0, 1/3, 1/2, 2/3 or 1. When $m = 1$, E^m is AE energy. When m = 1/2, E^m is the Benioff strain, which is the square root of energy release for a sequential rockburst. When m = 1/3 or 2/3, E^m is the m root of energy release for a sequential coal burst. When $m = 0$, Y is equal to N_+/N_-, where N_+ and N_- are the AE energies that occurred during the load/unload operations, respectively. The values of $m = 1/2$ and $m = 1$ are adopted, meaning that Y can be defined as

$$\begin{cases} Y = \left[\sum_{i=1}^{N+} E_i^{\frac{1}{2}}\right]_+ \Bigg/ \left[\sum_{i=1}^{N-} E_i^{\frac{1}{2}}\right]_- \\ Y = \left[\sum_{i=1}^{N+} E_i\right]_+ \Bigg/ \left[\sum_{i=1}^{N-} E_i\right]_- \end{cases} \quad (3.6)$$

3.4.4 Entropy Theory

Entropy is a thermodynamic concept and can be interpreted as a measure of disorder: the more disorganized a system, the higher its entropy. Entropy is a quantitative measure of uncertainty. Shannon, the founder of information theory, first systematically put forward a concept of measurement of information (Shannon 1948). Using the methods of probability and statistics, he took entropy as a measure of uncertainty or information of a random event, and solved the problem of quantitative measurement of information. For a probability test with N results, set the results with each discrete probability λ. Meanwhile, if

$$0 \leq \lambda_i \leq 1 \quad (i = 1, 2, \ldots, n) \quad (3.7)$$

$$\sum_{i=1}^{n} \lambda_i = 1 \quad (3.8)$$

Then

$$H(X) = H(\lambda_1, \lambda_2, \ldots, \lambda_n) = -k \sum_{i=1}^{n} \lambda_i \log \lambda_i \qquad (3.9)$$

where k is a constant and k $\geq$ 0; H is the information entropy, which is also called probability entropy or Shannon entropy.

Rockmass deformation and failure is a nonlinear dynamic process of going from a disordered chaos into an ordered status. Thus, the concept of information entropy and the relevant principle can be used in rock failure. For all dominant frequency values, the entropy values were calculated using Matlab software. The supposed dominant frequency is x(n), and n = 1–N, is the quantity of AE signal waveforms. The detailed process is as follows,

(1) Find and group the distribution range of x(n);
(2) Obtain the counts of dominant frequency data in each group at unit time interval, and solve the corresponding probability;
(3) Solve the entropy values using the information entropy formula.

3.4.5 Fuzzy Matter Element Theory

In order to analyze rockburst tendency more reasonably, the fuzzy matter element (FME) theory is applied to the evaluation of rockburst proneness. Cai (1994) devised the Matter Element Analysis (MEA) method with mathematics and experimental disciplines. In MEA, the three elements are events, features and values, which are used to describe these factors as the order basic element, and it is called matter-element. MEA is the study of matter-element variation and the system structure transforming, and the incompatibility problems are resolved if the magnitude of matter element are ambiguity. If the quantity of matter element is fuzzy, it constitutes a fuzzy incompatibility problem. FME was used to analyze and combine the fuzziness of corresponding quantity of things and the incompatibility between many factors, so as to obtain a new method for solving this kind of fuzzy incompatible problems. In recent years, this practical theory was being applied in the field of engineering technology, and many encouraging results were obtained.

There are many theories about rockburst tendency so far, such as stress method, rock integrity coefficient method, strength criterion etc. In these methods and the judgment index, if only the individual factors were considered, results may be one-sidedness and limitations. However, taking more factors into the complicated problem in rock engineering, many factors usually only have relative accuracy, and their relation with rockburst cannot be evaluated by “right” and “wrong”. Therefore, it is necessary to make full use of FME to consider the more influencing factors of rockburst comprehensively and to make a comprehensive judgment of its proneness.

3.4.6 Bayesian Theory and Network Model

A Bayesian identifiable model, with a statistical analysis heritage, is used to distinguish among different types of samples. The primary procedure is based on an artificial familiarity with known samples and possible attendant consequences. Firstly, the empirical probability and covariance of each classification is analyzed and calculated. Then, a discriminant function is formulated to grade samples. Finally, a posterior probability is calculated to verify the original evaluation. New samples were easily classified after being input into model (Ren and Yu 1999; Gao 1999).

Bayesian statistics is the basis of Bayesian discriminant analysis. The basic idea of Bayesian statistics is as follow: Firstly, we must have a certain understanding of research object. The prior probability distribution is used to describe this kind of knowledge, and the posterior probability distribution is obtained based on the prior knowledge of extracted samples, then can do a variety of statistics based on the posterior probability distribution. Finally, the Bayesian statistics can be used for discriminant analysis, and Bayesian discriminant analysis can be carried out as a basic method of statistical model in decision making, in all cases is not completely known for some unknown status with subjective probability estimation, the probability is modified by the Bayesians formula, finally using the expected value and correction probability to make decision. Bayesians theory has the uncertain knowledge expression ability and flexible reasoning mechanism, Bayesians' theory of rockburst tendency prediction model based on combining rockburst cases studied systematically in order to seek for effective prediction of rockburst. Combined with Bayesian distance discriminant analysis, a multi-parameter and multi-dimension rockburst predicting models can be established to overcome the limitations of single factor and individual difference.

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