An Overview of Fault Rockburst in Coal Mines

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Abstract. Fault rockburst has great harm and fault activation is the direct cause of its occurrence. On the basis of reviewing a large amount of literature, the examples of the fault rockburst in some coal mines in China, the distribution characteristics of in-situ stress in the vicinity of fault and various criteria and assessment methods of fault activation were systematically summarized and analyzed. The influencing factors of the fault rockburst disaster are expounded in terms of the features of fault, mining depth and layout of working face. The corresponding prevention and control measures were put forward based on the understanding of the mechanism of the fault rockburst, and it is believed that the early monitoring, warning and control of fault activation should be strengthened. Finally, the reasons why it is difficult to predict the fault rockburst accurately were discussed, and the problems existing in the current research and the directions for future research were pointed out.

1. Introduction

Rockburst is a nonlinear dynamic disaster occurring during coal mining and is caused by the redistribution of in-situ stress and the instantaneous release of accumulated energy of coal and rock masses induced by mining activities. It is usually characterized by suddenness, destructiveness and complexity, which poses a serious threat to the safe production of coal mines. Fault rockburst is one of the types of rockburst in coal mine, and it is a dynamic phenomenon of violent energy release due to the sudden relative displacement of faults caused by mining activities [1]. Faults in coal mines are generally well developed, which are indispensable geological factors in underground mining. A large number of on-site practices have shown that faults are important influencing factors that can induce rockburst in the mining and excavation working faces. The probability of rockburst in working faces or roadways will greatly increase when the mining and excavation working faces advance toward faults [2]. According to statistics, the number of rockburst occurring near fault and other fault structure zones accounts for more than 70% of the total [3]. Compared with other types of rockburst, fault rockburst has the characteristics of more energy release and higher magnitude, which makes it more destructive, more sudden and more influential [4]. As a result, the casualties, equipment damage and
roadway damage caused by fault rockburst are even more serious. They may even cause gas and coal dust explosions and roadway closures.

In view of the enormous impacts of fault rockburst, the rockburst has caused widespread concern in recent years. Based on study of a large number of relevant documents, the stress state near fault, the criteria for judging the activation of fault and the factors affecting the occurrence of the fault rockburst were systematically summarized and analyzed, and the prevention and control measures of the fault rockburst were proposed to achieve a more comprehensive approach of the rockburst and provide information for the early warning and prevention of the rockburst in the future.

2. Examples of fault rockburst in China
Coal mines at home and abroad have recorded the occurrence of fault rockburst. The first rockburst in China was in Shengli coal mine in Fushun, Liaoning province in 1933 [5]. At present, there are 177 rockburst mines in China, which are distributed in more than 20 provinces (cities or autonomous regions). Compared with coal-producing countries such as the United States and Australia, China has more complicated geological conditions of coal fields. Besides, fault structural zones in China are widely developed, and most of the rockburst mines are located in fault active zones. Practice has shown that fault structural zones directly or indirectly controls the occurrence of rockburst, so the problem of rockburst in coal mines in China is particularly acute. According to incomplete statistics, several coal mines in China have experienced fault rockburst disasters (Table 1), with the largest magnitude greater than 4.0. For example, the fault rockburst disaster in Yima mining area in Henan province is relatively serious. The F16 large-scale thrust fault is the main control fault in the mining area. Several mines in the mining area, such as Qianqiu and Yuejin coal mines, were affected by the activation of the F16 fault in the mining process, resulting that various degrees of rockburst disasters occurred. The magnitude of the rockburst occurred in Qianqiu coal mine in 2011 reached 4.1 [6].

| Name of coal mine         | Brief introduction of the occurrence of fault rockburst                                                                                                                                                                                                                                                                                                                                 |
|--------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Taiji coal mine, Liaoning| On June 28th, 1977, a 3.8 magnitude fault rockburst occurred in the mining area adjacent to the F10 fault, causing serious damage to underground production facilities. The F10 fault is a strike-slip fault with an inclination of 70 degrees and a strike of 20 degrees to the northeast.                                                                                                                                  |
| Jisan coal mine, Shandong | On December 16th, 2004, the 6303 working face of the mine pushed forward from the footwall of the SF28 fault to the fault, causing strong rockburst in the wind lane of the 6303 working face, followed by several small-scale rockbursts. The dip angle of the SF28 normal fault is 45 degrees and the drop of it is 2 m.                                                                                       |
| Muchengjian coal mine, Beijing | On April 26th, 2005, a strong rockburst occurred in the working face of the eastern wall of the mine that located between F3-1 and F3-2 major faults, causing casualties and serious spalling and blockage in many parts of the roadway.                                                                                                           |
| Huafeng coal mine, Shandong | On September 9th, 2006, 2 people died and 2 people were seriously injured when the F9 fault activated a rockburst with energy of $2.2 \times 10^7$ J in the drilling face of the 1410 upper drift of the mine.                                                                                                                                                                        |
| Baodian coal mine, Shandong | On August 1st, 2008, when the 103,upper,02 working face of the No.10 mining area of the mine was mined from the foot wall of XF-20 fault back to the fault, a strong mine shock occurred, with the roof falling off slag and coal dust flying. XF-20 fault is a normal fault with an inclination of 60 degrees and a drop of 2.5 m.                                                                 |
| Yuejin coal mine, Shandong  | On August 11th, 2010, a fault rockburst with the magnitude of 2.7 occurred on the 6303 working face in the mining area of the No.10 coal mine, causing casualties and serious spalling and blockage in many parts of the roadway.                                                                                                                                         |

Table 1. Examples of fault rockburst in some coal mines in China.
mine, Henan 25110 lower lane due to the activation of the F16 fault, causing 74 anti-impact supports to be damaged to varying degrees. The F16 fault is a thrust fault with an inclination of 60 to 65 and a drop of 40 to 120 m.

Qianqiu coal mine, Henan On November 3rd, 2011, 10 people were killed, more than 60 others were injured and some of the roadways were completely closed due to a 4.1 magnitude rockburst caused by the activation of the F16 fault during the excavation in the 21221 lower drift of the mine.

Junde coal mine, Heilongjiang On March 15th, 2013, a rockburst occurred under the influence of F1, F7 and L1 faults in the first sublayer of first section of the north layer of the third level of the mine, resulting in 4 deaths.

Xingcun coal mine, Shandong On August 5th, 2013, 4.4×10^5 J of rockburst occurred at 3302 transportation gateway drilling face of the mine due to activation of F22 fault. 4 people were injured and the roadway was damaged to varying degrees.

Gucheng coal mine, Shandong The 2106 working face of the mine is located at the footwall of F9 and DF4 inclined major faults. Several serious pressure anomalies occurred during the mining of the working face, causing serious roadway deformation and instability of some sections of the roadway.

Laohutai coal mine, Liaoning Frequent high-intensity mine earthquakes with magnitudes greater than 3.0 occurred near the normal faults of the mine, which seriously affects production.

In recent years, the proportion of fault rockburst in various types of rockburst has an upward trend with the increase of mining depth. Due to the complexity of the rockburst itself, especially the influence of complicated and changeable fault structures, the traditional understanding of rockburst mechanism can hardly explain the specific causes of the fault rockburst, which also increases the difficulty of understanding of the fault rockburst disasters, and thus, the fault rockburst is more difficult to predict. In a word, the fault rockburst is now facing the unclear understanding of the occurrence mechanism and improper prevention and control measures, which seriously affect the exploitation of coal resources. Therefore, it is necessary to effectively prevent and control fault rockburst disasters for safe production in coal mines.

3. Stress state near fault and fault activation criterion

3.1. Distribution characteristics of in-situ stress near faults

In-situ stress is the fundamental force causing fault activation. The occurrence of various types of engineering disasters in coal mines is mere representation. The essential controlling factor is the in-situ stress. The increase of stress level and the change of stress state are the fundamental factors. Therefore, it is necessary to study the distribution characteristics of in-situ stress near faults to predict the occurrence of fault rockburst. Generally, regardless of the size of a fault, it will have a certain degree of influence on the stress state in its vicinity, and the influence mechanism is more complex. This influence is mainly determined by the characteristics of the fault itself and the physical and mechanical properties of the coal and rock masses on both sides.

Hudson and Cooling [7] argued that discontinuous (such as fault) has a very serious local disturbance effect on the whole state of stress field, and the trajectory of the principal stress direction will change, as shown in Figure 1. As shown in Figure 1, Case 1 is an extreme case, that is, if the discontinuous is open (the elastic modulus of the filling material in the discontinuous is zero), then the direction of the maximum principal stress \( \sigma_1 \) becomes parallel to the discontinuous, and the direction of the minimum principal stress \( \sigma_3 \) changes to be perpendicular to the discontinuous, where \( \sigma_3=0 \). Case 2, if the filler in the discontinuum has essentially the same properties as the surrounding rock (the elastic modulus of both is equal), the directions of \( \sigma_1 \) and \( \sigma_3 \) may not be affected. Case 3 is another extreme case, that is, if the filler of the discontinuous is rigid (the elastic modulus of the filler in the
discontinuous tends to be infinite), then the $\sigma_1$ direction will change to be perpendicular to the discontinuous body and the $\sigma_3$ direction will change to be parallel to the discontinuous. In addition to the above three extreme cases, in other cases, the change in the direction of the principal stress is mainly determined by the physical and mechanical properties of the filling material in the discontinuous.

Figure 1. Effect of discontinuous on the stress state [7].

Grasping the in-situ stress characteristics near the fault is helpful to analyze the mechanical behavior of fault activation and is also crucial to study the evolution mechanism of fault rockburst. The studies have shown that the change of the stress state near the fault is very complicated, both the increase of stress and the decrease of stress. Moreover, the large fault will also cause the torsion of the direction of the maximum horizontal principal stress, making it parallel or oblique to the fault direction at a large angle, or even perpendicular to the fracture strike [8, 9]. In some cases, in-situ stress structure types at different locations at the same depth in the mining area are also quite different, which are mainly related to the changes of stress around the fault over time. Figure 2 shows in-situ stress variation with depth based on the in-situ stress measurement results [8] near the DF9 fault in Sihe coal mine, Jincheng mining area, Shanxi province. It can be seen that the maximum horizontal principal stress ($\sigma_H$) and the minimum horizontal principal stress ($\sigma_h$) near the fault decrease with increasing depth, which is inconsistent with the generally accepted that the in-situ stress increases linearly with depth as a whole.

Figure 2. Variation of principal stress with depth near DF9 fault in Sihe coal mine.

### 3.2. Fault activation criterion

#### 3.2.1. The criterion of Coulomb friction sliding.

The mechanical model of fault stress is shown in Figure 3. According to the principle of mechanical balance, the Coulomb friction sliding criterion (Eq. (1)) can be used to assess the stability of fault. This criterion is often used to study the shear failure of rock and determine the fault sliding. When judging the fault sliding, it is generally assumed that the...
fault plane cohesive force $C_0=0$. When the shear stress $\tau$ on the fault plane meets $\tau \geq \mu \sigma_n$, fault slip may occur.

$$\tau = C_0 + n\sigma_n$$  (1)

where $\tau$ is the shear stress on the fault plane, $C_0$ is the cohesive force of fault plane, $\mu$ is the friction coefficient of the fault plane, $\sigma_n$ is the normal stress on the fault plane.

3.2.2. Criterion of Coulomb friction sliding-Byerlee's law. The Coulomb friction sliding criterion combined with Byerlee's Law is widely used to assess the stability of faults in geology. According to the Eq. (1), after introducing the concepts of principal stress and effective stress, the ratio of the effective maximum principal stress to the minimum principal stress when the fault is at the critical friction limit can be expressed as Eq. (2) [10]. According to Anderson's fault theory [11], the tectonic stress characteristics of different types of faults can be determined. Combining Eq. (2) with Anderson's fault theory, the stress characteristics of reverse fault, strike-slip fault and normal fault can be obtained. According to Byerlee's law [12], $\mu$ is generally in the range of 0.6 to 1.0. If the crustal stress action reaches the frictional strength of the critically stressed fault, the frictional sliding will occur along the optimally oriented plane.

$$\frac{s_1 - P_0}{s_3 - P_0} = \frac{1 + m^2 + m}{m^2}$$  (2)

where $\sigma_1$ and $\sigma_3$ are the maximum and the minimum principal stress, respectively, $P_0$ is pore pressure.

3.2.3. The criterion of disturbance response. According to the criterion of disturbance response [1], if for any given $\varepsilon>0$, $\delta>0$ exists, so that when the disturbance displacement $\Delta a$ and fault dislocation response displacement $\Delta u$ that generated in the far field displacement of fault band and elastic rock system, meet the conditions that $\Delta a \leq \delta$, $\Delta u \leq \varepsilon$, then the fault band and elastic rock system is in a stable state. If the fault band and elastic rock system is in a certain state, no matter how small the displacement of the minor disturbance in the far field is, it will cause the infinite growth of the fault dislocation, that is, $\Delta a/\Delta u \to \infty$. This means that the fault band and elastic rock system is in an unstable state, and the fault will slip.

3.2.4. A new 3D fault activation evaluation method. Leclère and Fabbri [13] proposed a new 3D method to evaluate the activation of fault planes. This method can be applied to viscous or non-viscous faults in any direction, and there are no restrictions on the regional stress field. The method reactivates the fault plane using the calculated effective stress ratio ($Q$) to determine whether the fault plane is in a favorable orientation, unfavorable orientation or seriously misaligned orientation with respect to the surrounding stress field. The method also includes a graphical classification tool, which includes drawing the poles of the fault plane on the stereogram and dividing the boundaries of the three domains corresponding to favorable azimuth, unfavorable azimuth and severe dislocation. The division of these domains is based on $Q$ value, stress state ratio ($f$), static friction coefficient of fault ($\mu_s$) and cohesion of fault ($C_0$). The 3D fault activation analysis method can be applied to any geological stress tensor and fault properties.
When one of the above methods is used to judge whether a fault is activated, it may be accidental and random, and the reliability of the judgment result is questionable. According to the above discrimination methods, two or more of them can be selected to comprehensively predict the stability of a fault first, to know the stress state of the fault band and elastic rock system in advance, and then to judge whether the fault has the possibility of sliding.

4. Influence factors of fault rockburst disaster

4.1. Influence of fault characteristics on its own activation
The characteristics of the fault itself play a decisive role in its activation. Studies have suggested that the larger dip angle of a fault, the easier for the fault to activate [14]. The larger a fault plane area, the more strain energy can be stored, the more energy will be released during activation, and the stronger impact it will have [15]. For faults with large drop, the friction and dislocation between the hanging wall and footwall are relatively violent when the fault is formed, and high residual tectonic stress and energy are stored. When the fault is activated, it will generate high kinetic energy and the impact will be more destructive. The friction angle of a fault has a great influence on the sliding instability of the fault. With the increase of the friction angle of the fault, the maximum shear displacement, seismic moment, and seismic energy show a decreasing trend [16], which is beneficial to the stability of the fault and can reduce the risk of the rockburst of the working face. When the elastic modulus of the surrounding rock in a fault zone is relatively small, the fault is generally characterized by plasticity and low strength. The continuous creep activation often occurs, the stress fluctuates gently and there is no sudden stress reduction [17]. Thus, such fault activation releases less energy and is less likely to cause rockburst. On the other hand, when the elastic modulus of the surrounding rock in a fault zone is relatively large, the overall strength is relatively high, and the stress will suddenly drop after the peak value is reached. The fault breaks rapidly, causing viscous-slip activation [17], which releases high energy and easily induces rockburst. In addition, fault occurrence, fault stiffness, roughness of fault plane, and shear bulge angle also have great influence on fault activation [18, 19].

4.2. Influence of mining depth on fault activation
The mining depth has a significant effect on the mechanical behavior of faults. Sainoki and Mitri [20] stated that numerical values such as seismic moment, energy released during fault-slip, maximum shear displacement of fault, and slip rate increase with depth (Figure 4), among which the increase of the energy released during fault-slip is the most significant. It can be seen that with the increase of mining depth, the possibility of instability and sliding of faults will increase significantly.

Generally, once the fault slips during deep mining, the fault slip becomes more intense and releases high energy, thus the probability of occurrence of fault rockburst will greatly increase, and the damage caused will also be quite serious. Therefore, when large faults are encountered in deep mining, special attention should be paid to the mechanical behavior of the faults to strengthen monitoring and early warning so as to reduce the occurrence of fault rockburst disasters.

![Figure 4. Relation between behavior of fault and depth [22].](image-url)
4.3. Influence of working face layout on fault rockburst

The layout of working face has a great influence on the occurrence of fault rockburst. Some studies have shown that the probability and danger of rockburst occurring when the working face is located on the footwall of the fault is generally higher than that when the working face is located on the hanging wall of the fault [16, 21]. This is because the difference between the shear stress and the normal stress in the fault zone when the working face is located on the hanging wall of the fault and advancing toward the fault is generally smaller than that when the working face is located on the footwall of the fault and advancing toward the fault [16, 21]. Therefore, when the working face is located on the hanging wall, it may be more favorable to the stability of faults, and the risk of disaster caused by fault activation may be small. Figure 5 [21] shows the numerical simulation results of the fault slip displacement when the working face of Jisan coal mine in Shandong province is advanced on the hanging wall and the footwall of the fault. It can be seen that when the working face is close to the fault, the fault slip displacement at the footwall of the fault is much larger than that at the hanging wall of the fault.

![Figure 5. Comparison of fault slip displacement in Jisan coal mine [21].](image)

5. Fault rockburst prevention and control

For the prevention and control of fault rockburst, in addition to adopting conventional rockburst prevention and control methods (such as coal seam water infusion, destress blasting, strengthening roadway support and optimizing mining design), the most important thing is to reduce the risk of fault activation-induced disasters. The key is to focus on the prediction and control of fault activation, which requires understanding the geological information such as the mechanical characteristics, distribution and geometry of the fault structure in the mining area. The imaging and mapping of fault structures play an important role in the study of fault slip. A three-dimensional visualized fault model can be established using a 3D high-resolution seismic reflection system [22] to analyze fault activation characteristics. Gochioco and Cotton [23] used high-resolution seismic reflection techniques to locate faults in coal mines and estimated the sliding displacement of faults to ensure the safe production. In addition, monitoring the change trend of stress and strain in the fault zone and collecting the precursory information of fault slip are also necessary to prevent and control the fault rockburst. The fault sliding in the fault-affected zone is a nonlinear dynamic process of steady accumulation and unstable release of stress or elastic energy, and thus, the underground pressure behavior caused by fault activation is serious and violent. Therefore, the sharp increase in stress and subsequent stability can be considered as precursor information of fault slip [19].

With the increase of mining depth, faults, especially large ones, should be avoided as far as possible when mining areas are divided and mining working faces are arranged. If possible, the advancing direction of the working face should be made perpendicular to the strike of the fault, protective coal pillars should be left in the mining area to prevent the activation of the fault, and pressure relief treatment should be done well in advance to avoid high stress concentration. When working face has to pass through the fault, measures must be taken to prevent the hanging wall of the fault from being bare for a long time in a large area, to reduce the height of the mining section [24], and to optimize the roadway support design in the fault-affected zone to maintain the stability of the
roadway. Controlling the advancing speed of the working face can weaken the fault slip and is conducive to reduce the number of occurrences of fault rockburst [7]. In addition, early monitoring and early warning of fault activation should be strengthened, microseismic monitoring and mining stress monitoring should be carried out, and corresponding measures should be taken in time to deal with any danger signs.

6. Discussion
Since the dynamic process of fault slip lasts for a very short time, that is, it is almost instantaneous from the beginning to the end of fault slip, which makes it very difficult to know the fault activation mechanism and the failure movement law. Moreover, the mechanical mechanism for controlling faults is relatively complicated, which makes it difficult to accurately evaluate the stress changes in the fault band and elastic rock system. At present, it is impossible to accurately predict and estimate the occurrence and damage degree of fault rockburst. This is mainly attributed to the following two aspects [18]: (1) although many studies have been carried out on the measured data of the fault rockburst occurrence area through laboratory experiments and numerical simulation, it is still quite difficult to determine the physical and mechanical properties of the fault plane, and the dynamic behavior of fault slip has not been fully understood so far. (2) The geological structure of the mining area is relatively complicated. When the stress changes caused by mining activities are transferred to the surrounding areas, there is not only elastic deformation but also creep process, which causes the discontinuity of rock mass and geological structure to rupture, thus causing the secondary stress to be unevenly redistributed in the coal and rock mass around coal mine roadway and stope. In addition, the spatial distribution of the fault is complicated. The fault plane is irregular, and the activation mechanism of the fault is closely related to the roughness of the fault plane. The precursory information of the fault slip is not obvious. The above factors make it difficult to study the fault slip mechanism, thus causing the randomness and unpredictability of the occurrence of fault rockburst.

As mentioned earlier, the criteria for judging fault slip and the mechanism of fault rockburst disaster have been studied and results have been achieved. However, there are still some problems, which are summarized as follows: (1) the interaction mechanism between mining disturbance and fault activation is not clear. (2) The theoretical research on the movement of overburden strata and the evolution of stress field in fault areas is not perfect. (3) The change of normal stress and shear stress state on the fault zone caused by mining activities has not been analyzed in detail. (4) The interaction mechanism among mining disturbance, fault activation and rock and coal burst has not been studied. (5) Practical and effective evaluation methods for fault rockburst have not been established.

Fault rockburst occurs under the coupling of stress field, energy field, dynamic excavation and other factors. The relationship between the factors is not quite clear, which brings great challenges to the study of the mechanism of fault rockburst. In view of the particularity and complexity of the fault rockburst itself, the following aspects may need to be further studied: (1) based on the characteristics of the fault itself, the early warning technology for fault stability monitoring and its activation should be developed. (2) The effects of the characteristics of the fault structural zone on the stress distribution and elastic strain energy occurrence of the original rock. (3) Fault dynamic sliding criterion and the stope impact mechanism under combined dynamic-static load. (4) Dynamic evolution law of coal body stress in working face during fault slip transient process and the mechanism of fault slip and coal body impact failure. (5) The conditions for the occurrence of fault slip under different fault plane properties and the relationship between stress evolution and fault slip form. (6) It is necessary to establish a multi-field coupling model of fault rockburst to analyze the interaction mechanism between stress field and energy field in coal as well as the space-time migration law of energy evolution. (7) The establishment of risk assessment indexes system for fault rockburst. In summary, understanding how faults are activated under the influence of mining and the mechanism of fault rockburst is the fundamental to realize effective prevention and control of fault rockburst.
7. Conclusions
The primary cause of the fault rockburst disaster is the dynamic evolution of stress field and energy field caused by the mining disturbance, which destroys the original mechanical equilibrium state of the fault band and elastic rock system and results in fault reactivation. Fault characteristics, mining depth and working face arrangement play a key role in fault reactivation. The stress redistribution of surrounding rock caused by mining activities does not necessarily lead to fault rockburst. Only when mining disturbance causes stress concentration to a certain extent can disasters occur. The prevention and control of fault rockburst should focus on early prediction and control of fault reactivation. Monitoring the change trend of stress and strain in the fault zone and collecting precursor information of fault slip are necessary to prevent and control fault rockburst.

The dynamic evolution and development of stress and energy fields near the fault zone will become more and more complicated in deep mining, which brings great challenges to the study of the mechanism of fault rockburst. The current research on fault rockburst is not sufficient, and there are still many scientific issues that need to be solved in the future.

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