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Rockburst mechanism in soft coal seam within deep coal mines

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A B S T R A C T

A number of rockburst accidents occurring in soft coal seams have shown that the rockburst mechanism involved in soft coal seams is significantly different from that involved in hard coal seams. Therefore, the method used to evaluate rockburst in hard coal seams is not applicable to soft coal seams. This paper established an energy integral model for the rockburst-inducing area and a friction work calculation model for the plastic area. If the remaining energy after the coal seam is broken in the rockburst-inducing area is greater than the friction work required for the coal to burst out, then a rockburst accident will occur. Mechanisms of "quaking without bursting" and "quaking and bursting" are clarified for soft coal seams and corresponding control measures are proposed as the optimization of roadway layouts and use of "three strong systems" (strong de-stressing, strong supporting, and strong monitoring).

1. Introduction

Recently, rockburst accidents have become the main type of dynamic disasters influencing the safety of production in deep coal mines [1–4]. Such accidents usually occur within hard coal seams; however, they also occur in soft coal seams with an increase in mining depth, such as in the Shenbei, Laohutai, and Yiliyi coal mines in China (where strong rockburst accidents have occurred in the past few years). Studies have shown that the early-warning indexes for soft coal are vastly different from those for hard coal for similar geological conditions, and therefore, an analysis of the rockburst mechanisms and determination of early-warning methods for soft coal are of considerable importance to obtain production safety in deep coal mines [5–8].

Extensive research on the rockburst mechanism has been conducted in China and overseas. For example, Cook and Wawersik considered that coal acts as a support with a stiffness that is larger than the loader at the point at which rockburst occurs, and Kidybiński proposed indexes for classifying the potential liability of coal seams in relation to rockburst hazards [9–11]. In addition, Zubelewicz and Mroz proposed that rockburst accidents are caused by static and dynamic stresses [12]. Furthermore, a variety of theories have been put forward to explain the mechanisms involved in rockburst, such as stiffness theory, rockburst tendency theory, strength theory, "Voussoir Beam" and "key strata" theory, and overlying strata spatial structure theory [13–19]. However, these studies have mainly focused on the mechanism within hard coal seams, and thus, the mechanism for soft coal seams has not yet been clarified. Therefore, this paper analyzes the rockburst occurrence mechanism and criteria in soft coal seams by investigating a number of rockburst accidents that have occurred in soft mining mines and provides a theoretical basis for rockburst treatment in soft coal seams.

2. Comparison of rockburst phenomena in soft coal and hard coal seams with similar geological conditions

2.1. A microseismic phenomenon with large energy in soft coal seam

The longwall panel 3104 (LW 3104) in Chenmanzhuang Coal Mine, Shandong province, China, has an average depth of 700 m with a uniaxial compressive strength of 1.56 MPa (soft coal seam). A microseismic event with the energy of 1.0×10^7 J occurred on October 1, 2015 at a point 12 m above the roof and 88 m from the workface of LW3104, and 140 m away from the stopping line of Gob 3103, as shown in Fig. 1. Although the drill cuttings exceeded the standard, there were no phenomena of drill-drawing, drill-blocking, drill-butting, or coal-blasting. Rockburst accidents were not induced by this event.

2.2. A microseismic phenomenon with large energy in hard coal seam

The Longwall Panel 21141 (LW 21141) in Qianqiu Coal Mine within Henan province, China, has an average mining depth of 684 m with a uniaxial compressive strength of 18 MPa (hard coal

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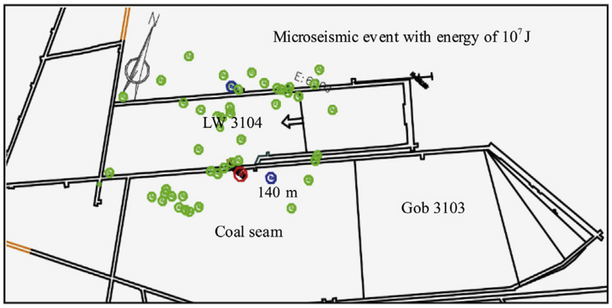

Fig. 1. Location of large energy microseismic event in Longwall Panel 3104 within Chenmanzhuang Coal Mine.

seam) (Fig. 2). A microseismic event with energy of 1.1×10^7 J occurred on May 27, 2010. During this event, most of the point props suffered damage and slid upward within the section between 400 and 710 m. The scratch length on the interface of arc beams and shed legs was up to 400 mm, and some screws were broken. The floor, which was situated 710 m away from the actual event venue, was heaved by 200 mm. In the lower roadway at a point 930 m away from the parking lot, 91 wooden point props and 20 single props were damaged and the anchoring and shotcreting skin dropped.

2.3. Analysis of rockburst phenomena within soft and hard coal seams

The mining depth, microseismic position, and associated energy in Chenmanzhuang Coal Mine are very similar to that of Qianqiu Coal Mine (Table 1). However, during the above-described events, the extent of damage in Qianqiu Coal Mine was much greater than that in Chenmanzhuang Coal Mine. From analysis, the rockburst mechanism and extent in soft and hard coal seams are very different in relation to their characteristics of "quaking without bursting" and "quaking and bursting". For example, the phenomenon of "quaking without bursting" has occurred in soft coal seams within the Shenyangsan Coal Mine in Shenyang province and the Chenmanzhuang Coal Mine. This phenomenon occurs when a super-thick coal seam is softened by injecting water and discharging gas, and a medium-hard coal seam becomes a soft coal seam. Then, when a quake with large energy occurs, the coal in the large loosened zone bursts out in relation to structural instability. The differences in rockburst mechanisms between hard and soft coal mines require differing preventative measures and these are mainly discussed in the following sections.

3. Energy calculation model for roadway rockburst

To evaluate rockburst danger from the perspective of energy, the rockburst-inducing area (the areas that accumulate enough elastic strain energy to induce rockburst) firstly needs to be defined. Furthermore, the elastic strain energy-calculating model for the rockburst-inducing area and the friction work-calculating model in the plastic area need to be established in order to derive the amount of energy required to induce rockburst.

3.1. Definition of rockburst-inducing area

To simplify the calculation and show general regularity, this paper uses a circular roadway after excavation as an example to analyze rockburst issues. After the roadway has been excavated, the stress in the surrounding coal alters from that of a three-dimensional stress state to one or two-dimensional stress state. The coal therefore becomes plastic due to a decrease in the

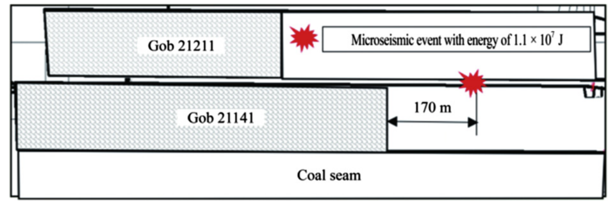

Fig. 2. Location of large energy micro seismic event in Longwall Panel 21141 within Qianqiu Coal Mine.

compressive strength. The three-dimensional stress state also reappears at a considerable distance from the roadway walls, and hence the coal becomes elastic due to the increase in compressive strength in this area (Fig. 3). In the plastic area, part of the elastic strain energy is consumed in plastic deformation, and for this reason the elastic strain energy density (elastic strain energy per unit volume) is not high enough to induce rockburst. In the elastic area, the critical stress, $k[\sigma_c]$, ($[\sigma_c]$ is the uniaxial compressive strength; k is the rockburst critical coefficient) intersects with the tangential stress, σ_t, forming a stress boundary with a radius D (Fig. 4) [20]. As a result, the elastic strain energy contained in the area between the plastic area boundary and the stress boundary represents the key energy for rockburst occurrence, and thus this area is defined as the rockburst-inducing area.

3.2. Integral model for elastic strain energy in rockburst-inducing area

If we assume that the coal in the elastic area is homogeneous and elastic, there is no creep and viscosity behavior, the original rock stress is equal in every direction, and all the surrounding rock behaves the same over an infinite length, then the method for plain strain problems can be applied and the elastic strain energy that induces rockburst can be studied using an analysis of a roadway section (Fig. 5).

The tangential stress work, W_t, and radical stress work, W_r, in the rockburst-inducing area can be deduced by stress analysis for the roadway cross section in Fig. 5.

$$\begin{cases} W_t = 2\int_0^{\pi}\int_R^D \sigma_t r \varepsilon_t d_r d_\theta \\ W_r = 2\int_0^{\pi}\int_R^D \sigma_r r \varepsilon_r d_r d_\theta \end{cases} \tag{1}$$

where σ_r, σ_t, ε_r, and ε_t are the radical stress, tangential stress, radical strain, and tangential strain, respectively; R the radius of the plastic area, which can be found in detail in literature pertaining to plasticity and elasticity; and D the radius of the rockburst stress boundary, i.e. the circle radius of intersection points of σ_t and $k[\sigma_c]$. If $\sigma_t = k[\sigma_c]$, D can be deduced as [21].

$$D = R\sqrt{\frac{k[\sigma_c] - \sigma_0}{\sigma_0 \sin\varphi + c\cos\varphi}} \tag{2}$$

where σ_0 is original rock stress; c the cohesive force; and φ internal friction angle.

Substituting Eqs. (2) into (1), W_t and W_r can be obtained,

$$\begin{cases} W_t = \frac{\pi}{E}\Big[(1-\mu)\sigma_0^2(D^2-R^2) + 4\sigma_0(\sigma_R-\sigma_0)R^2\ln\frac{D}{R} \\ \qquad + \Big(1+\mu\Big)(\sigma_R-\sigma_0)^2\Big(R^2-\frac{R^4}{D^2}\Big)\Big] \\ W_r = \frac{\pi}{E}\Big[(1-\mu)\sigma_0^2(D^2-R^2) - 4\sigma_0(\sigma_R-\sigma_0)R^2\ln\frac{D}{R} \\ \qquad + \Big(1+\mu\Big)(\sigma_R-\sigma_0)^2\Big(R^2-\frac{R^4}{D^2}\Big)\Big] \end{cases} \tag{3}$$

where E is the coal elasticity modulus; μ Poisson's ratio; and σ_R the stress on the interface of the plastic area and elastic area.