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Numerical simulation of rock-burst relief and prevention by water-jet cutting

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ABSTRACT

The applications in coal mine rock burst prevention using water jet cutting technology (WJCT) have progressed slowly. In this paper we analyzed the possibility and reasonableness of WJCT application to rock burst relief and prevention, used the ABAQUS software to simulate the distributive characteristics of stress and energy fields suffered by hard coal roadway wallrock and the internal relationships of the fields to the instability due to WJC on roadway wallrock, and conducted field WJCT tests using electromagnetic radiation (EMR) measurement technology. The results showed that WJCT can unload rock burst effectively by inducing stress release and energy dissipation in coal mass near its cut slots; its annular slots also can decrease rock burst risks through blocking or weakening stress and energy transfer in coal mass. The horizontal radial slots and annular vertical slots may cause “the beam structure” and “the small pillar skeleton”, and “the layered energy reservoir structure”, respectively, which lead to an increase in stress concentration and energy accumulation in coal element mass near the slots. The reasonable design and optimization of slots' positions and their combination not only can significantly reduce the scope of stress concentration and energy accumulation, but also can destroy coal mass structure on a larger scale to force stress to transfer deeper coal mass, eventually avoiding high intensity and large-scale rock bursts. The field tests of WJC for pressure relief using EMR verified the above conclusions.

1. Introduction

Coal, as China's primary source of energy, accounts for about 70% of primary energy consumption and plays a vital role in economic development [1]. In recent years, with coal demand increasing, the coal mining depth increases at a rate of about 10 m per year, while coupled with which, the occurrences of rock bursts significantly increase and seriously threaten safety production [2,3].

Water jet cutting technology (WJCT) has been investigated theoretically and practically by many scholars. A high pressure water jet is directed to hard materials, as coal, rock, and the like, and can destroy their original states and structures, or controllably break rocks [4–8]. For the underground coal seams subject to great stress, WJC can destroy them locally and play a good role in pressure relief. Moreover, water media applications not only avoid producing static sparks, but also prohibit or precipitate coal dust. Thus, WJCT has been widely used in the prevention of coal mine disasters, especially coal and gas outburst. Lin et al. [9,10] found through numerical simulations that the cut depth with a high pressure abrasive jet cutter is up to 700–800 mm; Chang [11] found that WJC of 70 MPa can cut out a kerf of 1.7 m width and 50 mm depth in coal-like materials; Li et al. [12] studied the relationship between the notch depth and the jet pressure and found that when the pressure of water jet reaches about 20 times as the compressive strength of test samples, the depth tends to be a certain constant, hardly changing with the jet pressure. Lu [13], Liu [14] and Liang [15] used WJCT for the gas extraction, outburst relief, etc. in soft coal seam, and achieved a series of good results.

Different from coal and gas outburst, rock burst generally occurs in the hard coal seams that store large amounts of elastic energy. The key to prevent from outburst is to destroy the structure of coal mass in which great stress is concentrated and to avoid further accumulation of a large quantity of elastic energy [16–18]. At the same time, because the hard coal has the good capability to transfer stress and energy, it is necessary to take measures to weaken the capacity for the prevention of rock outburst [19–21]. It is clear that the rock burst prevention technology based on WJCT is more complex than coal and gas

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outburst prevention. Therefore, although some scholars [22,23] have preliminarily applied WJCT in rock burst prevention, the poor rock burst relief effect has widely limited its application.

To further study WJC application for the prevention and control of rock burst, in this paper, we first theoretically analyzed WJC pressure relief in hard coal seams, then numerically simulated the distributions of stress and energy fields in roadway wallrock after WJC pressure relief through ABAQUS software, investigated the reasons for poor pressure release, and solved the difficulty through the optimization of different kerfs combination. At last, we used coal rock EMR measurement technology to verify the effect of WJC pressure relief with two roadway field tests. The research is of significance for WJC pressure relief and rock burst prevention in hard coal mining production.

2. Analysis of WJC pressure relief

2.1. Analyses of stress and energy of coal element

A small element is chosen in coal mass, assuming that it satisfies the duality of scale. On the one hand, its size is small enough macroscopically so that it can be seen as a material point of continuum damage mechanics and its macroscopic stress–strain field can be regarded as homogeneous. On the other, its size is large enough mesoscopically so that it contains sufficient information of mesoscopic structure and reflects the statistical average properties of materials [24,25]. These ensure that it is still based on the basic laws of theory of elasticity–Hooke's law, for the purpose of ensuring the strictness of mathematical derivation.

The size and shape of the small element acted by an external force are changed, the stress of any one three dimensional stress state, σ_1, σ_2, and σ_3, can be decomposed into two parts, one is the average stress applied upon the three directions σ_{ave} [26]

$$\sigma_1' = \sigma_2' = \sigma_3' = \sigma_{avg} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \quad (1)$$

The other is the stresses borne respectively by the three directions, $\overline{\sigma}_1 = \sigma_1 - \sigma_{avg}$, $\overline{\sigma}_2 = \sigma_2 - \sigma_{avg}$, and $\overline{\sigma}_3 = \sigma_3 - \sigma_{avg}$, where $\overline{\sigma}_1$, $\overline{\sigma}_2$, and $\overline{\sigma}_3$ are called the stress deviators of the given states of stresses σ_1, σ_2, and σ_3. The corresponding average stress $\overline{\sigma}_{avg}$ is

$$\overline{\sigma}_{avg} = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3 - 3\sigma_{avg}) = 0 \quad (2)$$

Under the action of the average stress σ_{avg}, the shape of the small element is invariant, only its volume changes, thus its strain energy density (here only the changes in the volume can cause the changes in the strain energy density) can be expressed as

$$\upsilon_V = \frac{1-2\mu}{6E}(\sigma_1 + \sigma_2 + \sigma_3)^2 \quad (3)$$

Under the actions of stress deviators $\overline{\sigma}_1$, $\overline{\sigma}_2$, and $\overline{\sigma}_3$, because the corresponding average stress $\overline{\sigma}_{avg}$ is zero, the volume of the small element is invariant, only its shape changes, then its strain energy density (here only the deformable energy density) can be expressed as

$$\upsilon_d = \frac{1+\mu}{6E}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \quad (4)$$

The strain energy density υ equals the deformed energy density υ_d plus the volume-changed energy density υ_V, that is,

$$\upsilon = \upsilon_d + \upsilon_V = \frac{(1+\mu)}{6E}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] + \frac{(1-2\mu)}{6E}(\sigma_1 + \sigma_2 + \sigma_3)^2 \quad (5)$$

It is clear from Eq. (5) that the energy stored in the coal mass element is closely related to three-dimensional states of stresses. Meanwhile in accordance with the least energy principle [27], the energy stored in the condition of one-dimensional stress or two-dimensional stresses is smaller than the energy in the condition of three dimensional stresses. Therefore, for the purpose of pressure relief, it is possible for us to use water jet to cut kerfs in the coal mass to change its stress state and to induce its internal energy to be dissipated or released.

2.2. Pressure relief by water jet (WJ)

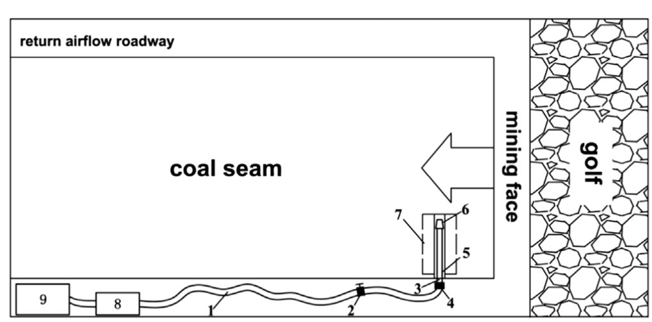
Statistics show [28] that more than 70% of rock bursts occurred in the regions affected by mining in the front of working face. In the bilateral coal mass of the roadway outside the advance supports of working face, the roadway excavation causes the stress redistribution, thus from the roadway sides deeper into the coal mass in order form the pressure relief zone, the stress concentration zone, and the original stress [29]. At the same time, the part of coal mass still has to suffer a certain mining disturbance. In fact, a large amount of elastic energy accumulated in the coal mass of the stress concentration area (in general 5–12 m away from the roadway side) is the direct source of energy to rock bursts.

Pressure relief from the coal mass of this area through WJC can be implemented by the coal seam WJ pressure relief system whose main equipments include the high-pressure pumping station, high pressure piping and high-pressure nozzle, and whose auxiliary equipments include the water storage tank, high pressure valves, fixture and guiding devices, etc. Schematic of the coal seam WJ pressure relief system is shown in Fig. 1.

At present, in order to achieve pressure relief in the coal mass of the stress concentration area, the slotting method used currently at mining sites is to cut the horizontal radial and vertical annular slots on its roadway sides [30], as shown in Fig. 2.

The impact of the water jet on coal mass can cut a kerf of a certain width and depth in coal/rock mass, turning the primary three-directions force state of the kerf's surrounding coal mass to the two-directions one, thereby resulting in changes in the energy storage states of small coal elements in the vicinity of the kerf, simultaneously providing a free space of elastic recovery for coal mass, and thus releasing the excess energy stored previously in the three dimensional state of stress.

It can be seen from Fig. 2(a) that the important roles of the radial slotting are (1) the impact of the water jet directly breaks the nearby coal mass, making it release its pressure and dissipate its excess energy; (2) the cutting kerf provides a great space for coal to deform and further induce the deeper compressed coal



1-High-pressure pipe; 2-High-pressure valve; 3-Guiding device; 4-Fixed device; 5-Hole; 6-High-Pressure sprinkler; 7-Slot; 8-High-pressure pump; 9-Water tank

Fig. 1. Schematic of coal seam WJ pressure relief system.