Tunnelling and Underground Space Technology 32 (2012) 34–43

Contents lists available at SciVerse ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Deep-hole directional fracturing of thick hard roof for rockburst prevention

Hu He [a,b], Linming Dou [b,*], Jun Fan [b], Taotao Du [c], Xinglin Sun [b]

[a] School of Resource and Earth Science, China University of Mining and Technology, Xuzhou, Jiangsu 221008, PR China
[b] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Xuzhou, Jiangsu 221008, PR China
[c] Beijing Mining Research Institute, China Coal Research Institute, Beijing 100013, PR China

ARTICLE INFO

Article history:
Received 5 January 2012
Received in revised form 16 April 2012
Accepted 1 May 2012
Available online 2 June 2012

Keywords:
Directional fracturing
Rockburst
Hard roof
Initial groove
Microseismic

ABSTRACT

Thick hard roof in coal mines is usually a significant factor that induces dynamic disasters, such as rockburst. This study introduces a new technology called directional hydraulic fracturing characterized by cutting out an initial groove in the borehole and then injecting high pressure liquid to break the rock. The abutment pressure on the groove tip and fracture criterion is worked out based on the fracture mechanics taking fluid seepage into consideration. Computational simulations revealed that the vertical compressive stress changed to tension immediately after high pressure liquid injected into the fracturing hole, the concentration factor up to 5 that can easily rupture the roof and reduce the rockburst hazard at the same time. The seamless steel tubes are used instead of high pressure hose and conveyed into fracturing holes by geological drill to the designed locations, so as to break through the depth limitation and make the whole process automated. In situ applications at two longwall faces of LW6305 and LW5307 show that the depth can easily reach to 20 m and the fracture radius more than 13 m within half an hour, the efficiency and security are greatly improved. We can determine whether the roof is split by observing the pressure changes. The pressure of liquid during fracturing process can be divided into three stages: dramatically ascending, descending and stable, corresponding to crack initiation, propagation and dissemination, respectively. Drilling bits method and microseismic system validate prevention effects of this technique notably so that lead to a foundation for large scale popularization and application in China coal mine.

1. Introduction

As we all know that China has been the largest coal production country, but China is also the most severe mining areas suffered from the dynamic disasters of rockburst or coal bump, accounted for one third of the total in the world (Li et al., 2007; Dou et al., 2009). In the past few decades rockburst disasters occurred in more than 100 collieries caused numerous injuries, fatal accidents and property loss. But majority of people engaged in coal industry had little knowledge on this dynamic phenomenon, so rockburst is always a research hotspot and difficulty of rock mechanics (Dou et al., 2006). Researchers at home and abroad carried out studies mainly focused on three aspects that mechanism, prediction and control methods. Great achievements had been obtained especially the breakthrough work of Cook that gave us better understandings on the essential process of rockburst (Cook, 1965). Afterwards many theoretical and numerical models have been developed in mechanism analysis (Salamon, 1984; Gibowicz and Kijko, 1994; Fujii et al., 1997; Dou and He, 2001; Blake and Hedley, 2001; Sharan, 2007; Zhu et al., 2010; He et al., 2010). However, in the mining field the engineers most concerns about how to control and eliminate the hazards efficiently and safely since no monitoring method has proven entirely reliable for dangerous degree prediction though a variety of countermeasures are used (Salamon, 1984; Brady and Rowell, 1986; Srinivasan et al., 1997; Mansurov, 2001).

The prevention methods of rockburst can be classified into two categories: long-term strategy and instant destress. Long-term strategy includes layout of workface and coal seam exploitation sequence, but the mining system can be hardly changed once formed, so during the coal mining destress must be carried out aiming to the dangerous areas. Hard thick roof is usually the main factor that causes excessive stress concentration and induces dynamic strata behaviors. Theoretical analysis and in situ seismic monitoring results indicate that most sources of rockburst are located in strata with high strength and integrity especially thick sandstone immediately overlying the seam, so hard thick sandstone roof is treated as the sign of rockburst in many countries (Dou et al., 2006). Blasting and water injection are traditionally used to control the hard roof, however these two means have obviously inherent defects, for example, blasting can only be utilized in low gas mines and misfire is very hard to tackle, as for water injection, the effect will be whittled down greatly due to high compactness and low permeability

* Corresponding author. Tel.: +86 13705206814; fax: +86 051683995904.
E-mail address: hehu_cumt@126.com (L. Dou).

0886-7798/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tust.2012.05.002

Nomenclature

σ_1, σ_3	the maximum and minimum principal stress in the rock mass (MPa)
$\sigma_x, \sigma_y, \tau_{xy}$	normal and shear stress components acted on the groove (MPa)
β	the angle between σ_1 and σ_y (°)
σ_b	the tangential stress at any point on the groove (MPa)
m	the axis ratio of the ellipse
α	the eccentric angle between the line from a point to the center with the X-axis (°)
R_t	the tensile strength of the hard roof (MPa)
μ	the dynamic viscosity of the high pressure liquid (Pa s)
l	the crack length (m)
$\overline{V}$	the liquid velocity (m/s)
k	the permeability of liquid in the hard roof ($\mu m^2 \times 10^{-6}$)
P'	the pore pressure (MPa)

(Dubinski, 1994; Board et al., 1992; Tang, 2000; Klishin, 2006). New technology that much more effective than traditional methods with little risk must be developed with the increasing requirements of safety. In this study the application of deep-hole directional hydraulic fracturing at Jining No. 3 coal mine in Shandong province is presented, series of difficulties and key parameters are solved to make this technique practical and can take the place of blasting in the near future.

2. Method of directional fracturing of hard roof

The hydraulic fracturing technology has been researched both in China and abroad, great achievements have been obtained after decades of development (Beach, 1980; Lenoach, 1995; Garcia and Sousa, 1997; Papanastasiou, 1997; Ruiting, 2006; Mofazzal and Rahman, 2008), but we found that most of the previous studies focused in the field of petrol exploitation and in situ stress measurements (Fairhust, 1964; Haimson and Fairhurst, 1970; Ito et al., 1999; Rahman and Joarder, 2006). However applications of hydraulic fracturing in coal mine are just in its infancy currently, and mainly used to fracture the coal seam so as to increase permeability of gassy coal seams, improve hard thick top coal cavability and prevent coal and gas outbursts (Huang et al., 2007). Hydraulic fracturing of the coal seam is conducted by drilling a circle hole in the coal and then injecting liquid directly. Usually cracks can fissure with low hydraulic pressure since the coal seam is relatively soft compared with roof. If we plan to control hard thick main roof using hydraulic fracturing, the pressure of the liquid will be increased vastly and probably exceed the pump ability, moreover the propagation of the main cracks and airfoil branch fissures are determined by the stress field, so it is difficult to realize the directional slice of the roof.

The directional fracturing method is proposed by Polish experts of the Central Mining Institute mainly aiming to disintegrate the compact rocks, but few research papers that introduced the mechanism and technical parameters systematically have been reported (Yan et al., 2000; Du et al., 2010). Fig. 1 shows that the essence of directional fracturing is the generation of a spatially oriented fracture in the rock mass and under the impact of high pressure liquid injected into the borehole, the cracks propagate from the tips of the oriented fracture thereby dividing the rock layers into blocks or plates with determined sizes and forms. Such a process is owing to the generation of the so-called initial groove with exactly spatial orientation in the borehole surroundings. This initial groove delimits the direction of fracture propagation and its rise is induced by the high pressure liquid. Both the integrity and strength of hard roof are weakened after fractured, as a result the sudden roof falling with large area is avoided and the rockburst danger reduced ultimately.

2.1. Mechanism of directional fracturing propagation

The crack of the initial groove under rock stress and liquid pressure is a typical category of fracture mechanics, so we establish a simplified plane model to analyze the stress distribution and the failure criterion around the initial groove, as shown in Fig. 2.

Based on the relationship of principal stress and the stress components around the ellipse fracture of elasticity theory, one can obtain the equations as follows:

$$\sigma_y = \frac{1}{2}(\sigma_1 + \sigma_3) - \frac{1}{2}(\sigma_1 - \sigma_3)\cos 2\beta, \quad \tau_{xy} = -\frac{1}{2}(\sigma_1 - \sigma_3)\sin 2\beta, \quad \sigma_x = \sigma_1 + \sigma_3 - \sigma_y \tag{1}$$

where σ_x, σ_y and τ_{xy} are the x and y-direction stresses component acted on the groove, respectively, σ_1 and σ_3 are the maximum and minimum principal stress, β is the angel between σ_1 and σ_y. The tangential stress σ_b at any point on the crack wall can be expressed by the Inglis equation (Wang et al., 2008) as:

$$\sigma_b = \{(\sigma_y - P_0)(m(m+2))\cos^2\alpha + \sigma_x((1+2m)\sin^2\alpha - m^2\cos^2\alpha) + \tau_{xy}(2(1+m)^2\sin\alpha\cos\alpha)\}/(m^2\cos^2\alpha + \sin^2\alpha) \tag{2}$$

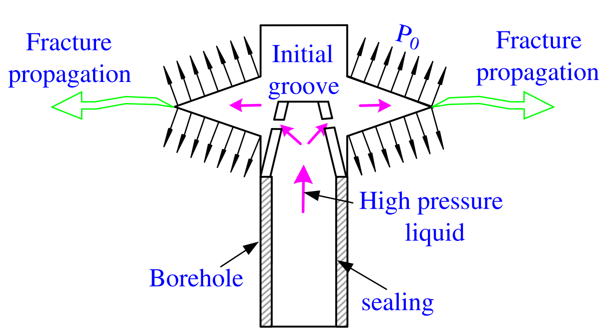

Fig. 1. Essence of directional fracturing.

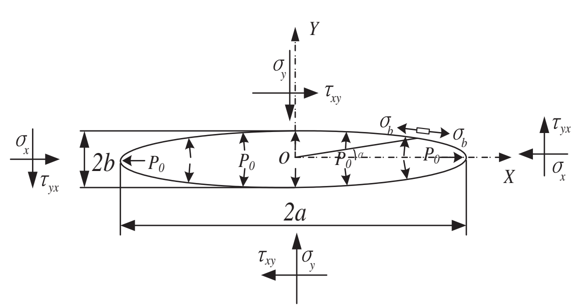

Fig. 2. Mechanical model of the artificial fracture in the hard roof.