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Investigation of the formation mechanism of coal spallation through the cross-coupling relations of multiple physical processes

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ABSTRACT

Coal spallation is a visible product of outburst, and it represents a unique failure type for coal. A theoretical analysis of coal spallation was constructed to study its formation mechanism. Then, physical experiments and numerical simulations were performed to determine the physical features of coal spallation and evaluate the theoretical analysis. In addition, the effect of gas, stress and coal strength on coal spallation was discussed. The results show that coal spallation is a comprehensive product of multiple physical factors, including stress, gas and the coal strength. The formation process is related to stress transfer and mechanical behavior changes, gas migration and the evolution of the coal strength. Coal is eventually subjected to tensile failure, and the mechanical condition for coal spallation requires that the gas pressure difference ($p_i - p_a$) near the exposed surface is enough to overcome the tensile strength (σ_t). The gases in coal provide the power necessary for coal spallation; thus, coal gas promotes plastic failure and is the leading factor for tensile failure. Stress is the leading factor for plastic failure and has a great influence on the extent of coal spallation. Meanwhile, with an increase in the coal strength, which represents the resistance to coal spallation, the acreage of the plastic area decreases, and thus, a greater pressure difference is required for tensile failure.

1. Introduction

Coal and gas outburst, hereinafter referred to as outburst, is one of the major disasters that threaten safe production in coal mines. Outburst is a complex dynamic failure process that emits a large amount of coal (rock) and gas into the production space in a short time.[1–3] Over the years, due to space limitations, only outburst features outside of outburst holes have been observed from the spots where such disasters occurred.[4] The features behind outburst holes are seldom recorded, although they are the key to studying the mechanisms of outburst. Therefore, laboratory simulations constitute a common method employed to verify the physical processes of outburst by replicating their characteristics.[5,6] Among those features, coal spallation is one of the most obvious features observed behind an outburst hole.[7,8]

The mechanism of coal spallation is complex and varied, and it is similar to the mechanism of outburst. Ding et al. found that coal undergoes tensile failure and breaks into spherical shells under the effects of gas seepage. Wu et al.[9] analyzed the spallation structure via an outburst simulation and found that there are three types of coal spallation, namely, ")", "I" and "(" types. According to the plastic deformation localization theory, Pan[10] deduced an equilibrium relationship between the work and energy increments when a coal shell deforms and established a catastrophe model of the coal shell. A crushing wave theory of outburst was proposed by Khristianovich,[11] who illustrated that unloading waves are involved in the failure of coal. Based on a one-dimensional outburst simulation, Song[12] explained the mechanism of coal spallation and proposed a characteristic length equation.

In the abovementioned studies, coal spallation was considered the comprehensive result of stress, gas and coal strength factors, and it was closely associated with the formation of a high gas pressure gradient near the exposed surface. Further analyses on the mechanisms of coal spallation focused on the mechanical conditions of spallation either qualitatively or semi-quantitatively. However, the evolution of these physical factors during coal spallation and the cross-coupling relations among them have not been analyzed completely. Some of the major associated problems can be summarized as follows. How do the transfer of stresses, the mechanical behavior of coal, and the coal strength

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change during spallation? Additionally, how does the coal permeability evolve? Furthermore, how does gas migrate, and how does a high gas pressure gradient form?

In this paper, a theoretical analysis of coal spallation is established by considering stress transfer and mechanical behavior changes, gas migration and the evolution of the coal strength. The formation mechanism of coal spallation is investigated comprehensively and systematically to analyze the cross-coupling relations among the factors. Physical experiments and numerical simulations are adopted to determine the physical features of coal spallation and evaluate the theoretical analysis results. In addition, the effects of the presence of gas, the magnitude of stress and the coal strength on coal spallation are discussed comprehensively.

2. Theoretical analysis

Coal spallation is a comprehensive result of multiple physical factors, including the magnitude of stress, the presence of gas and the coal strength. The formation process of spallation is related to stress transfer and mechanical behavior changes, gas migration, and the evolution of the coal strength.[13,14]

2.1. Stress transfer and mechanical behavior changes

Once coal is exposed during a period of outburst, the stress within the coal will be quickly transferred, which will be accompanied by the concentration of stress in certain regions ahead of the exposed surface. The distribution of stress can be divided into three areas, namely, the original state area, the concentrated stress area and the unloading stress area, as shown in Fig. 1. Similarly, the mechanical behaviors of coal are different in these areas.

2.1.1. Original state area (I)

In this area, the stress and gas in the coal are undisturbed by outburst activity, and the coal is in a state of stress equilibrium (Fig. 1). The simplified stress equilibrium equation for a basic unit under the combined effects of a surface force and a body force is[15]

$$\sigma_{ij,j} + F_i = 0 \tag{1}$$

where σ_{ij} is the stress tensor ($i, j = x, y, z$), which is also known as the surface force, MPa; and F_i is the body force component in the i-direction, consisting of numerous influences, including the gas pressure gradient ($p_{,i}$) and gravity gradient ($g_{,i}$), MPa/m.

The presence of gas in coal modifies the mechanical response of

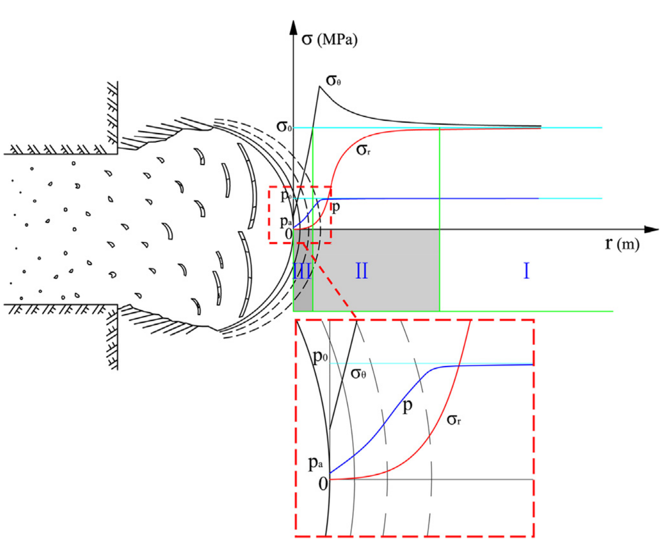

Fig. 1. Distribution of stress in the coal ahead of the exposed surface.

coal. Among the different types of gases, free gas affects the effective stress in coal and adsorbed gas imposes a non-mechanical action on coal.[16–18] Based on Terzaghi's law, the effective stress can be expressed as

$$\sigma'_{ij} = \sigma_{ij} - \beta\delta_{ij}p \tag{2}$$

where σ'_{ij} is the effective stress, MPa; p is the gas pressure, MPa; δ_{ij} is the Kronecker delta; β is the effective stress coefficient, $\beta = 1 - \frac{K}{K_m}$; K is the bulk modulus of coal, MPa; and K_m is the bulk modulus of the coal matrix, MPa.

The strain-displacement relationship can be defined as

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{3}$$

where ε_{ij} is the coal strain tensor ($i, j = x, y, z$), and $u_{i,j}$ is the displacement component.

Based on the elastic theory, the constitutive relation between the stress and strain is

$$\sigma'_{ij} = 2G\varepsilon_{ij} + \frac{2G\nu}{1-2\nu}\varepsilon_v\delta_{ij} - K\varepsilon_v^s\delta_{ij} \tag{4}$$

where G is the shear modulus, MPa; ν is Poisson's ratio; ε_v is the volume strain, $\varepsilon_v = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$; ε_v^s is the adsorption-induced volume strain, $\varepsilon_v^s = \frac{\varepsilon_{lv}^s p}{p + p_L^s}$; ε_{lv}^s is the maximum adsorption-induced volume strain; and p_L^s is the Langmuir pressure of the adsorption-induced strain, MPa.

2.1.2. Concentration stress area (II)

Disturbed by outburst activity, the initial stress equilibrium in this area is destroyed, and the stress quickly transfers. As a result, the tangential stress becomes concentrated and the radial stress decreases ahead of the exposed surface (Fig. 1). This stress transfer leads to a decrease in the coal yield strength. When the tangential stress exceeds the coal yield strength, the coal undergoes plastic failure.[19]

The Drucker-Prager (DP) matching Mohr-Coulomb (MC) yield criterion is chosen for the failure criterion of coal[20,21]:

$$F - (\sqrt{J_2} + \alpha_{DP} I_1 - k_{DP}) = 0 \tag{5}$$

where I_1 is the first stress invariant, MPa; J_2 is the second deviator stress invariant, MPa^2; and α_{DP} and k_{DP} are coefficients that are defined by the cohesion c and the friction angle φ:

$$\alpha_{DP} = \frac{2\sin\varphi}{\sqrt{3}(3 - \sin\varphi)} \tag{6}$$

$$k_{DP} = \frac{6c\cos\varphi}{\sqrt{3}(3 - \sin\varphi)} \tag{7}$$

As reported in the literatures,[22,23] the mechanical behavior of coal is relatively stable in the pre-peak region. However, the stress-strain behavior in the post-peak region is extremely complex.

To study the complete stress-strain behavior of coal, the relevant mechanical processes should be simplified and the inelastic strain between the yield point and the peak point should be ignored.[24] In the pre-peak region, the coal is subjected to compressional strain with an increased tangential stress. When the plastic failure of coal occurs, the coal experiences an apparent strain softening behavior characterized by a gradual transition from a peak failure criterion to a residual one.[24]

A type of strain softening behavior for an unconfined compressive test is shown in Fig. 2. The transition from a peak stress to a residual stress is governed by the softening parameter γ^p.[25] Therefore, the full stress-strain process can be described as follows: the elastic regime exists when $\gamma^p = 0$; strain softening behavior occurs if $0 < \gamma^p < \gamma^{p*}$; and the residual state begins at $\gamma^p \geq \gamma^{p*}$, where γ^{p*} is the transition value of the softening parameter from which the residual stage begins.

The incremental softening parameter ($\dot{\gamma}^p$) depends on the plastic strain increments and is commonly expressed as[26]: