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Mechanical failure mechanisms and forms of normal and deformed coal combination containing gas: Model development and analysis

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ABSTRACT

In coal mining, coal seams often contain several normal coal layers and deformed coal layers in the same region. However, the existence of deformed coal may promote the occurrence of coal and gas outbursts. To analyze the role of failure of different combinations of deformed coal on coal and gas outbursts, force analysis of normal and deformed coal combinations containing gas was carried out, and the expressions of interfacial stress induced by uncoordinated horizontal deformation were first derived in this paper. The results showed that the additional interfacial stresses are affected by the external stresses, internal gas pressure, gas sorption-induced swelling deformation and mechanical parameters of coal and that the additional interfacial stresses on the normal coal and deformed coal are equal and opposite. Then, based on the Mohr-Coulomb criterion and uncoordinated deformation, the mechanical failure mechanisms and forms of combinations containing gas under ideal conditions were analyzed. We found that there are seven failure forms for the combination containing gas, and in most cases, the destruction of the combination is caused by the structural failure of deformed coal. Finally, the failure mechanisms of the combination due to mining were discussed using the parameters from the Qinshui Basin. The results showed that failure is more probable at the interface between the deformed coal and normal coal bodies and that the existence of deformed coal can promote the damage of normal coal. These research results can help us to better understand the role of mechanical failure in coal and gas outbursts within combinations, and provide a theoretical basis for the control of coal and gas outbursts.

1. Introduction

China boasts the largest number, scale and losses of coal and gas outburst disasters worldwide [1,2]. To meet the needs of economic growth, large quantities of coal must mined in the future [3], which will result in an increase in the mining depth of coal and more severe gas outburst disasters. Although the processes surrounding coal and gas outburst disasters are very complex, they occur under conditions requiring a certain amount of deformed coal in the regions of coal and gas outbursts [4–6]. Because of tectonic movement of the coal seam under the ground, intense plastic deformation may occur in some areas [7] and may form deformed coal layers. Deformed coal layers do not exist in isolation, and there are often several normal coal layers and deformed coal layers in the same place.

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After mining, the stress environment of coal and rock will be changed [8], which causes the coal to be damaged and even leads to coal and gas outbursts; thus, the failure of coal is the primary prerequisite for coal and gas outbursts. In a combination of normal and deformed coal, the strength of deformed coal is far less than that of normal coal; thus, deformed coal is the weak link of such a coal combination [9]. Moreover, deformed coal accelerates the development of failure of the combination and can even cause gas outburst disasters to occur. Beginning in the 1980s, scholars [10] found that the deformation and failure of this combination are affected by the adjoining rock or coal due to their different mechanical parameters. Depending on the different materials of the combination, they can be divided into rock-rock combinations, coal-rock combinations and coal-coal combinations.

Among the three types of combinations, rock-rock combinations were the first to be researched. Duffault [10] conducted research on the theory and numerical simulation of rock-rock combinations. Experimentally, Tziallas et al. [11] carried out mechanical experiments on mudstone and sandstone combinations with different proportions under uniaxial and triaxial stress states, and an empirical formula for predicting the compressive strength of combinations based on experimental data was obtained. From a theoretical perspective, Xian et al. [12] established a theoretical model of isotropic rock combinations and discussed the influence of parameters on the mechanical strength of combinations under different stress states. Li et al. [13] calculated the interfacial stress and analyzed the mechanical failure modes of rock-rock combinations under a uniaxial stress state.

Rocks can influence the deformation and failure of other rocks. Additionally, there are interaction effects between coal and rock owing to the lower mechanical strength of coal. The study of coal and rock combinations can help us to better understand the mechanisms of rock outbursts. Dou et al. [14] obtained the electromagnetic emission rule of coal and rock combinations during the loading process, the results of which were applied to the prediction of rock outbursts. To better understand the failure mechanisms of coal and rock combinations, a series of methods, including theoretical analysis, laboratory tests and numerical simulations, were used. The failure mechanisms of coal and rock combinations are governed by both external and internal influence factors [15]. The external factors mainly refer to the stress states of the combinations, while the external factors primarily refer to the properties of the combinations. Zuo et al. [16] found that splitting was the main failure form for combinations under a uniaxial stress state, while shear was the main failure form under a tri-axial stress state. In addition, the effects of rock strength, combined manners and inclined angles of combination on the failure mechanisms were researched by some scholars [17–19]. Based on the strain energy equivalency principle, Zhao et al. [20] established an analytical model for the failure criterion of combinations and discussed the failure forms of combinations that are affected by the interface strength, rock thickness and stress state.

Previously, greater effort was made to study rock-rock combinations or rock-coal combinations, and research regarding the failure mechanisms of coal-coal combinations was scarce. Using the simulation method, Li and Tan [21] analyzed the effects of the position of deformed coal on the failure of a combination, and they found that the intensity of coal and gas outbursts would be much stronger when the deformed coal constitutes the middle of the combination. Duan et al. [22] found that with the increase of the thickness of the deformed coal of the combination, the scale of a coal and gas outburst disaster would increase. Because the existence of deformed coal can make coal and gas outbursts much more probable [23,24], it is necessary to undertake a more comprehensive survey of the mechanical failure mechanisms of normal and deformed coal combinations containing gas, which can help to better understand the role of mechanical failure in coal and gas outbursts and to provide a theoretical basis for the control of coal and gas outbursts.

There is always a certain magnitude of interface cohesion between underground coal and rock [25]; therefore, this study was conducted based on the assumption that an interface cohesion between normal coal and deformed coal exists. In this paper, the uncoordinated horizontal deformation was first defined and deduced, and the interfacial stress expressions were obtained. Then, the mechanical failure mechanisms and forms of combinations containing gas under ideal conditions were analyzed, and seven failure forms for normal and deformed coal combinations containing gas were found. Finally, the failure mechanisms of normal and deformed coal combinations due to mining were discussed using parameters from the Qinshui Basin.

2. Force analysis

2.1. Force analysis of normal and deformed coal bodies

Normal coal and deformed coal are both assumed to exist within a homogeneous and isotropic medium, and the two coals are closely connected to one another between the layers. Before destruction, the two coals are regarded as one body during analyses of the stress state and the deformation of the combination. Biot's coefficient of coal is deemed to be 1. As shown in Fig. 1, the coal combination is affected by the external stresses in three directions, the internal gas pressure and the gas sorption-induced swelling deformation.

In this paper, the coal body is defined as the coal far away from the interface, and the coal interface is defined as the coal closest to the interface. For the coal bodies far away from the interfaces, their deformation cannot be affected by the deformation of other coals; thus, they can maintain their respective characteristics of deformation similar to a single coal body. The force conditions of normal and deformed coal bodies far away from the interfaces are the same, and the stress expressions can be expressed as:

$$\begin{cases} \sigma_{1n} = \sigma_{1d} = \sigma_1 - p \\ \sigma_{2n} = \sigma_{2d} = \sigma_2 - p \\ \sigma_{3n} = \sigma_{3d} = \sigma_3 - p \end{cases} \quad (1)$$