

## Mechanism and Criteria of Dilatancy-Induced Disaster of Coal Containing Gas

Zuxiang Hu<sup>1,\*</sup>, Sheng Wu<sup>1</sup> and Zhiqiang Yin<sup>2</sup>

<sup>1</sup> School of Mining & Safety, Anhui University of Science and Technology, Huainan 232001, China

<sup>2</sup> School of Civil and Mechanical Engineering, Curtin University, Perth 6102, Western Australia, Australia

Received 19 August 2017; Accepted 21 November 2017

### Abstract

The key to the prevention and control of coal and gas dynamic disaster is the mastery of its mechanism. However, plenty of factors induce coal and gas dynamic disasters, and the mechanism is complex, especially the dilatancy of coal and rock by mining. The main control factors of dynamic disasters change, thereby making such disasters difficult to manage. The mechanism of dilatancy caused by coal crack was analyzed based on the physical mechanical characteristics of gassy coal to explore the mechanism of coal and gas dynamic disaster induced by coal dilatancy in the working face. The energy evolution characteristics of the coal face during dilatancy stage were studied, and the safety evaluation index of disaster caused by the dilatancy was presented. Results show that the coal dilatancy in the working face depends on the force environment and the physical mechanical properties of coal. With the increase in initial gas pressure, elastic modulus, compressive strength, and critical stress value of the dilatancy are reduced, resistance to deformation and destruction of the coal containing gas is weakened, and the mechanical phenomenon of dilatancy easily occurs. The change gradient of gas pressure and gas expansion energy can increase with the increase in initial gas pressure in the dilatancy moment. The safety evaluation index increases from 0.09 to 1.29 when the initial gas pressure reaches 3 MPa. This finding shows that the safety evaluation index of disaster caused by the dilatancy has a nonlinear positive correlation with gas pressure. The dynamic disaster can only be caused by the effect of the mining action at a gas pressure of 3 MPa. This study provides a theoretical reference for the prevention and control of coal and gas dynamic disasters.

*Keywords:* Coal containing gas, Mechanical characteristic, Dilatancy, Gas pressure gradient, Safety evaluation index, Dynamic disaster

### 1. Introduction

With the increase in mining depth, crustal stress and gas pressure increase significantly, permeability of coal seam worsens, complexity of the structure increases significantly, and dynamic disasters of coal and gas become serious. Comprehensive gas control measures for coal have been implemented not only in the first deep coal seam without pressure relief but also in high-stress regions; however, coal and gas outburst disasters occur frequently, thereby posing a serious threat to the safety of deep coal rocks containing gas [1]. This study focuses mainly on the change in the mechanical behavior of deep coal containing gas. In comparison with the shallow part, the deep coal and rock mass is characterized by high stress, gas, and temperature, and a complex mechanical environment; as a result, this mass exhibits obvious nonlinear mechanical properties[2]. The mechanical phenomenon of dilatancy occurs easily due to the action of mining disturbance. The dilatancy of coal containing gas instantly breaks down the dynamic equilibrium state of gas desorption and adsorption and causes changes in the main factors of coal and gas outburst (gas pressure and stress), which easily leads to dynamic disasters that involve coal and gas[3]. Coal and gas dynamic disasters are the comprehensive results of energy

accumulation, dissipation, and release of coal and rock mass[4-5]. Effective calculation, storage, and dissipation of energy in coal containing gas and reasonable prediction of coal and gas dynamic disasters are issues that must be addressed urgently.

The energy released from coal rocks containing gas mainly comes from the work performed by external force and the internal energy of gas; the work performed by external force to coal and rock mass is mainly stored as elastic strain energy[6]. At present, the method of calculating the elastic strain energy of coal and rock mass is mainly based on two kinds of energy impact tendency index[7]. The premise of the first type of index is that it does not consider the plastic deformation before the peak strength of coal and rock mass, but the proportion of plastic deformation before the peak value of coal rocks containing gas is far greater than that of negligible grade. The premise of the second type of index is to conduct cyclic loading and unloading tests below the peak strength of coal and rock to obtain elastic and plastic strain energy. The elastic and plastic deformation energy of the peak strength of coal rocks cannot be obtained accurately because of the difficulty of achieving cyclic loading and unloading tests of peak strength. The deformation of coal rocks containing gas in the process of dilatancy and destruction is mainly plastic. The amount of plastic deformation is increased because of the influence of gas. If the plastic deformation is neglected, then the calculation error of the elastic strain energy of coal rocks containing gas will lead to the misjudgment of coal and gas dynamic disasters.

\*E-mail address: zxhu@aust.edu.cn

ISSN: 1791-2377 © 2017 Eastern Macedonia and Thrace Institute of Technology. All rights reserved.

doi:10.25103/jestr.106.21

The existing elasto-plastic strain energy calculation method should be improved to eliminate inaccurate predictions of coal and gas dynamic disasters. On the basis of a study on the mechanical properties of coal containing gas dilatancy, a new method of calculating elasto-plastic strain energy is presented, and the mechanism of dilatancy-induced disaster of coal containing gas is studied. This study aims to establish a foundation for further research on the mechanism of coal and gas dynamic disaster.

## 2. State of the Art

Studies on gas-solid coupling dilatancy of coal containing gas are still in the initial stage. Domestic and foreign scholars have conducted considerable research on the mechanical properties of rock dilatancy and obtained rich research results. For example, Bridman[8] first discovered the dilatancy of rocks and considered it a precursor to macroscopic destruction of rock. Matsushima[9] and Handin[10] conducted a granite and dolomite traditional three-axis test, and they found that dilatancy occurs at the same confining pressure conditions. Takahashi and Haimson[11] found that the dilatancy start point and volumetric strain gradually decrease with the increase in the intermediate principal stress. L. R. Alejano[12] considered that expansion of dilatancy depends on material properties and confining pressure. Professor Zongji Chen[13] studied tunnel, roadway deformation, and rock dilatancy behavior, and found that under the action of external load, the dilatancy of rock would exacerbate its physical expansion and produce a combined effect so that the free expansion rate after dilatancy was much larger than the static condition rate. In studies on the dilatancy of coal, Shugang Cao, Xuefu Xian, academicians, and other experimental[14] studies found that the dilatancy of coal stress and residual strength is low relative to the high strength of rock. Professors Pan Liyou and Jinquan Jiang et al.[15] established a dilatancy model of ground pressure without gas impact. In sum, numerous research results have been obtained on the dilatancy characteristics of rock, but few findings have been obtained on the dilatancy characteristics of coal containing methane with relation to coal containing gas and disaster. Guangxiang Xie and other studies discovered that the dilatancy of mining coal seam is likely to induce the release of storage energy to cause dynamic disaster, which shows that the mechanical properties of coal rocks containing gas are significantly different from those without gas. Studying the mechanism of dynamic disasters that involve coal rocks containing gas on the basis of mechanical characteristics of coal rocks without gas is neither scientific nor reasonable, as this approach results in inaccurate prediction of coal and gas dynamic disaster.

The process of energy accumulation and release is the main cause and internal driver of the occurrence of dynamic disasters. Dynamic disasters occur when coal rock contains more energy than the dissipative energy required to destroy coal and rock. Therefore, accurate calculation of the accumulation of elastic strain energy in coal rocks containing gas is the key to the effective prevention and control of coal and gas dynamic disasters. Methods for calculating the elastic strain energy of coal rocks without gas have been studied more than methods that calculate the elastic strain energy of coal rocks containing gas. For example, R. E. Goodman[17,18,19,20] proposed the energy impact index on the basis of full stress strain curve of rock

measured on a rigid test machine. The left half of the area around the curve represents the elastic deformation energy that accumulated before rock failure, and the right half of the area represents the plastic deformation energy consumed after rock failure, taking the peak intensity as a boundary. A. Kidybinski et al. [21,22,23] proposed the use of the elastic strain energy index (wet) of rock as an index of rock burst tendencies, which is defined as loading the rock specimen to 0.7 Rb to 0.8 Rb first and then unloading to 0.05 Rb when uniaxial compressive strength (Rb) test is performed. The strain energy released from unloading is considered the elastic strain energy, which can be stored as plastic strain energy. Domestic and foreign scholars have conducted relative studies on the basis of the calculation method of elastic strain energy in the above two classical rock energy impact indexes. He ping Xie et al. defined the concept of unit releasable elastic strain energy in their study on the inherent relationships between energy dissipation, energy release and rock strength, and overall failure during rock deformation and failure [24]. Tian bin Li et al. analyzed the principle of energy accumulation and release in the rock failure process on the basis of the water cut effect of rock energy evolution, and the calculation method of elastic strain energy was defined from uniaxial and conventional triaxial compression tests [25]. Previous studies mainly focused on the calculation of elastic strain energy of coal free gas, in which the calculation method does not change the plastic strain before the peak strength of rock is neglected. Such studies also focused on the concept of calculating elastic strain energy obtained by cyclic loading and unloading test of peak strength. A considerable difference is apparent between the mechanical deformation characteristics of the hard rock and the coal rocks containing gas. Coal rocks containing gas are prone to dilatancy mechanical behavior, and plastic deformation is the main form of deformation during its dilatancy to failure. If the plastic deformation is still ignored, then it is bound to cause the calculation error of the elastic strain energy of coal rocks containing gas. Therefore, in accordance with the stress-gas pressure-strain curve of coal containing gas, a new method of calculating elasto-plastic strain energy is proposed on the basis of the experiment of gas-solid coupling of coal containing gas. The method scientifically divides the stage of elastic-plastic deformation of coal rocks containing gas and effectively solves the problem of calculation error of elastic strain energy due to plastic deformation being ignored. Criteria for dilatancy-induced disaster of coal containing gas are established according to the law of conservation of energy. Further research is recommended on the mechanism of dilatancy-induced disaster of coal containing gas. This study aims to establish the foundation for further research on the mechanism of coal and gas dynamic disasters.

The rest of this study is organized as follows: In Section 3, the fracture propagation and evolution process of mining coal and rock is studied, a new method of energy calculation is proposed, and the mechanism and mechanical criterion of dilatancy are established. The analysis of the result according to the judgment index is presented in Section 4. The conclusions are presented in Section 5.

## 3. Methodology

### 3.1 Heterogeneity of coal

Coal is transformed by plant debris through complex biochemical and physical chemistry. Coal in the process of

formation is controlled by sedimentary environment, diagenesis, metamorphism, and late tectonic movement of the earth's crust effect, thereby resulting in spatial distribution of various attributes and internal heterogeneity changes, which manifest as coal heterogeneity and anisotropic medium, as shown in Fig. 1.

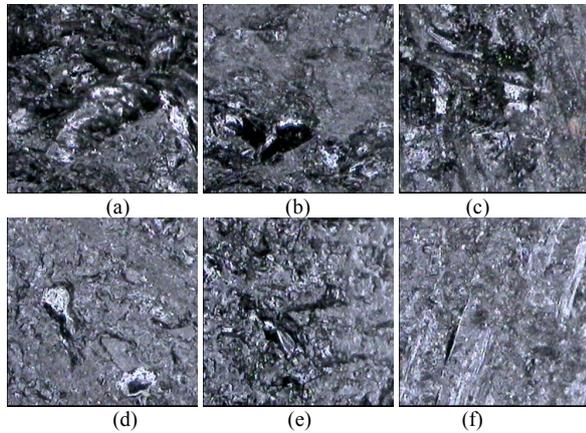


Fig.1. Specular scan of 6 coal seam samples in the Xie Qiao coal mine

Fig.1 shows a coal specular scan of the Xie Qiao coal mine at the 11316 working faces. From the view of the mesostructure, the structure of coal in different coal samples is different, and the density and stratification of a certain area of coal sample show significant differences, as shown by the red marks in Fig. 1(a) to 1(c). Tuberculosis (see Fig. 1[c] and 1[d]) and tectonic fissures (see Fig. 1[d]) in local areas of coal samples are apparent. Results show that the heterogeneity of coal is obvious even in the same depth, the same coal seam, or even the same local occurrence position. The heterogeneity of coal leads to a considerable difference in its mechanical properties, as shown in Fig. 2.

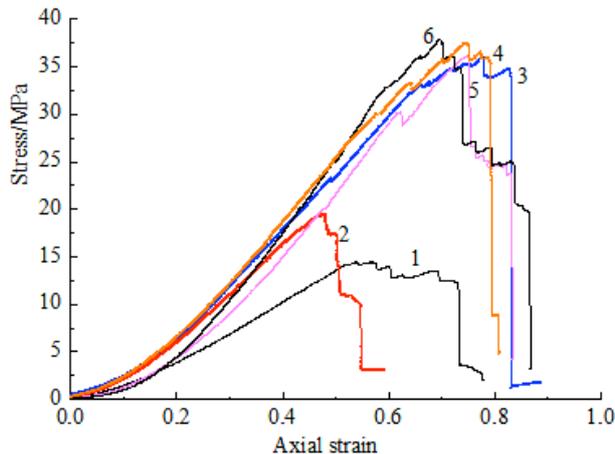


Fig. 2. Stress-axial strain curve of 6 coal seam samples in Xie Qiao coal mine

The curve of the initial loading compaction phase of the coal sample does not overlap, the partial stress–strain curve is steep, and the compressive strength of the coal sample is different, as shown by the stress–axial strain diagram. Results show that the characteristics of internal voids in coal mass are different and the homogeneity is low, thereby resulting in the different deformation characteristics of the coal mass after the force.

The heterogeneity of coal leads to its anisotropy and the physical property difference of coal seam without location, which has a negative influence on the safe mining of coal

seam. The state of stress in the coal mining face has undergone the dynamic process from the increase in the original rock stress, the vertical stress, and the confining pressure reduction to the unloading of the mining process under the influence of mining disturbance. Stress distribution in the stress relief zone, stress concentration zone, and original stress zone appear in the coal face in front of the work face. The deformation of the coal mass is different even under the same stress due to the heterogeneity of the coal, resulting in an uneven stress distribution. The homogeneity (stress concentration) of the coal mass in front of the working face results in more complicated deformation of the coal mass under the influence of mining.

**3.2 Fracture propagation and evolution of mining coal and rock**

Under the action of coal mass heterogeneity and high differential stress, the stress rise area of the coal face and the local area of the coal mass produce tensile stress, which cause the primary micro-crack and secondary crack to expand and connect with each other. The pore volume increases after fracture propagation and connectivity in the coal and rock. As the work surface advances, a gradual increase in the coal mining stress leads to crack propagation and results in dilatancy before the peak of the coal face. The redistribution of the stress before the dilatancy of the coal and rock usually results in the expansion of the slag in the dilatancy zone so that the coal and rock in some structural or weak parts begin to deform or expand, resulting in the change of coal and rock in the intermittent fissure surface and the production of macro-fracture. In general, the stress concentration area of the coal and rock in the front excavation face moves forward with the advancement of the working face. The dilatancy area before the peak force should experience vertical stress unloading, thereby resulting in coal and rock stress redistribution, which may occur because of non-mean inelasticity in some parts of the formation of a differential deformation caused by tensile stress concentration. If the tensile stress concentration area is greater than the tensile stress of coal and rock tensile or shear strength, then initial fracture of coal and rock in the beginning, tensile stress concentration area of coal rock body with primary fissures, expansion of cracks, and nonlinear growth of coal and rock volume deformation nonlinear growth occur as a result.

**3.3 Disaster-causing mechanism of coal mining dilatancy**

The cracks in coal are nonlinear and prone to dilatancy due to the heterogeneity and differential stress in the coal face. However, whether dilatancy of coal mass is dependent on the force environment and the physical mechanical properties of the coal is an issue that needs to be investigated. Results show that the gas pressure changes abruptly when the coal mass is dilated, and dynamic disasters such as coal and gas outburst are easily induced. However, coal mining dilatancy is not necessarily a dynamic disaster. The dilatancy of the elastic deformation of the storage capacity and the dilatancy of gas expansion energy can break and cause the coal to be thrown away; this condition indicates whether the dilatancy of coal mass can cause disasters.

**3.3.1 Deformation energy of coal and rock**

At present, the calculation methods for the load deformation energy of coal and rock mainly include the energy release index and elastic strain index methods [11,12], as shown in Fig. 3.

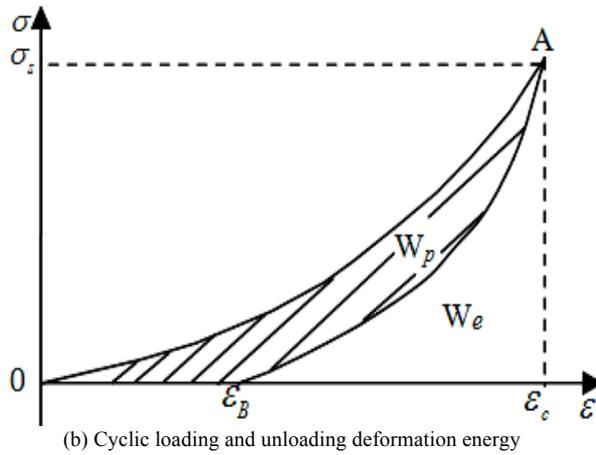
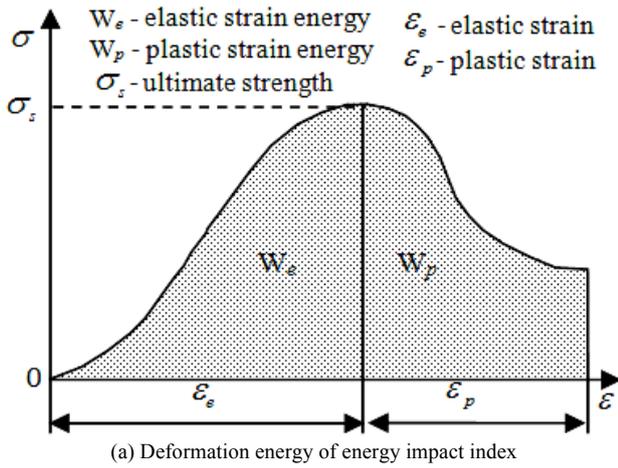


Fig. 3. Commonly used elastic deformation energy calculation diagram

Fig. 3(a) shows that the energy release index method takes the area value between the axial stress-strain curve and the abscissa axis before the peak strength of coal and rock as the elastic strain energy. The elastic and plastic deformation occurred before the peak load of coal and rock reached its peak strength. Energy loss caused by plastic deformation is neglected because the respective energy cannot be calculated separately. Hence, the calculated results are larger than the actual stored elastic strain energy. If the elastic strain energy index method is used to calculate the elastic strain energy, then loading and unloading experiments should be conducted, and the rebound curve of loading and unloading shown in Fig. 3(b) should be used to calculate the elastic strain energy. However, the loading and unloading experiment can only test the pre-peak intensity, such as peak intensities of 70% and 80%. Loading and unloading experiments on peak intensity cannot be conducted. Hence, the actual deformation energy calculated is not comprehensive, and the calculation results are biased.

The mechanical behavior of dilatancy occurs before the peak stress of coal and rock containing gas. In accordance with the mechanical characteristics and definition of coal mass dilatancy, the volumetric strain of coal and rock containing gas changes from compression to expansion, and the expansion and evolution of the internal fissure lead to the aggravation of the coal and rock damage. The deformation of coal and rock containing gas is mainly plastic during dilatancy to failure. On the basis of the stress - volume strain curve of coal and rock, this study takes into account the three-dimensional deformation of axial and radial direction of coal and rock, which can reflect the actual

deformation state of coal mass. The elastic strain energy of coal and rock storage is calculated based on the critical stress of expansion. The main consideration is that the deformation of coal and rock is mainly plastic after dilatancy. Scientific classification of the elastic plastic strain stage and an effective solution to the inability of the axial total stress-strain curve or the loading and unloading test to accurately and comprehensively calculate the elastic strain energy are possible.

As shown in Fig. 4, the first compression after expansion of the dilatancy deformation process occurs in the coal and rock containing gas. Strain deformation after dilatancy is mainly plastic. Therefore, the critical area (A point) of gassy coal is bounded, and the area of volume strain curve (0-A segment) and surrounded abscissa axis is considered elastic strain energy, namely,  $S_{0AB}$ . The volume strain curve (A-0 section) and the axis of the surrounding area become the plastic deformation energy, namely,  $S_{0BAC}$ , after the dilatancy of the critical point.

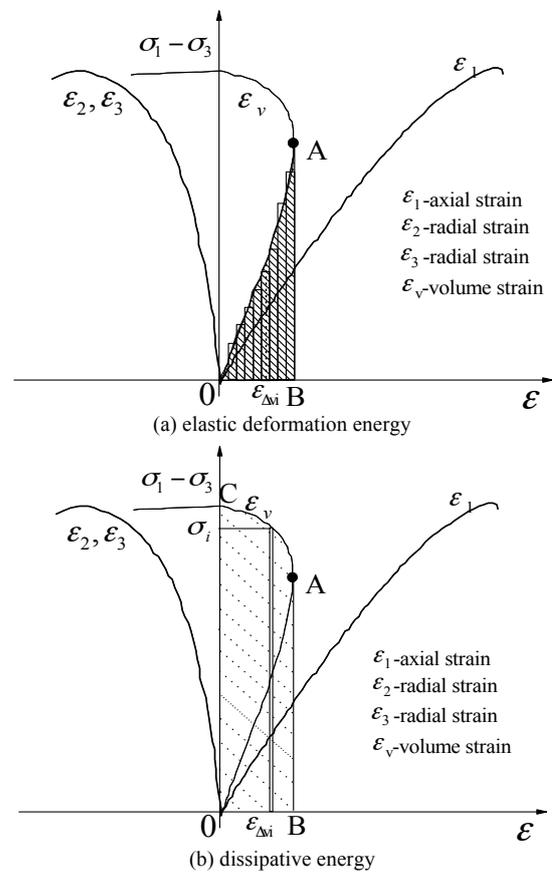


Fig. 4. Stress-strain curve of coal and rock

Hence, the storage elastic deformation energy  $W_e$  is represented as

$$W_e = \int_0^{\epsilon_B} \sigma_i d\epsilon_v \quad (1)$$

where  $\epsilon_v$  is the volume strain value,  $\epsilon_B$  is the strain value that corresponds to the dilatancy critical point, and  $\sigma_i$  is the differential stress, in MPa.

An analysis of Fig. 5 shows that the shape of the shadow is a curved triangle. Therefore, the area of

$S_{0,AB}$  using the principle of definite integral is calculated, the shape of  $S_{0,AB}$  is divided into  $n$  small trapezoids, and each small trapezoid can be regarded as a small rectangle. Small rectangular areas are considered curved triangle areas, and the actual calculation according to Equation (2) is given as

$$W_{e,p} = \sum \sigma_i \varepsilon_{\Delta vi} \quad (2)$$

where  $\sigma_i$  is the differential stress, and  $\varepsilon_{\Delta vi}$  is the corresponding unit volume strain value of  $\sigma_i$ , in MPa.

### 3.3.2 Disaster-causing mechanical criterion of coal mining dilatancy

According to the energy conservation law, disaster caused by dilatancy of gassy coal mass is the elastic deformation energy stored before dilatancy and the gas expansion energy formed by dilatancy into the working surface of the coal body crack expansion of the dissipated and kinetic energies when the coal body loses its stability and is thrown away, that is,

$$W_e + W_p = W_k + W_r \quad (3)$$

where  $w_e$  is the elastic deformation energy of coal mass, in J;  $w_p$  is the gas expansion energy, in J;  $w_k$  is the dissipated energy in the process of expansion to the failure of coal, in J; and  $w_r$  is the kinetic energy when coal is thrown, in J.

Equation (3) shows that if the elastic deformation energy of coal storage and gas expansion energy are greater than the energy dissipated by coal fragmentation, then the coal body will possess a certain residual kinetic energy, which will lead to coal and gas dynamic disasters. The safety evaluation index of disaster caused by the dilatancy of coal mass can be expressed by  $R_k$ , as shown in Equation (4) below

$$R_k = \frac{(W_e + W_p)}{W_k} \quad (4)$$

Substituting Equation (2) into Equation (4) yields

$$R_k = \frac{(W_e + W_p)}{W_k} = \frac{\left( \int_0^{\varepsilon_B} \sigma_i d\varepsilon_v + \frac{PP_2V}{(n-1)P_0} \left[ \left( \frac{P_1}{P_2} \right)^n - 1 \right] \right)}{\int_{\varepsilon_E}^{\varepsilon_B} \sigma_i d\varepsilon_v} \quad (5)$$

where  $P$  is the coal seam gas pressure, in MPa;  $\varepsilon_B$  is the gassy coal dilatancy critical point volumetric strain;  $\varepsilon_E$  is the gassy coal peak point volume strain;  $n$  is the Adiabatic coefficient;  $V$  is gas emission per ton of coal,  $m^3/t$ ;  $P_0$  is Standard atmospheric pressure, in MPa;  $P_1$  is the coal seam gas pressure before dilatancy, in MPa;  $P_2$  is the coal seam gas pressure after dilatancy, in MPa, and  $\sigma_c$  is the gassy coal ultimate strength, in MPa.

Equation (5) indicates that the coal containing gas in the working face is under the action of mining stress, and its storage energy can increase when it reaches the required energy of dilatancy instability, that is,  $R_k \geq 1$ , which reaches the critical value for dynamic disaster. When  $R_k < 1$ , the energy storage of coal and rock is less than the energy

needed for the destruction and dissipation of energy, and dynamic disaster does not occur.

### 3.3 Test equipment and sample

An experimental study on the mechanical characteristics of coal containing gas is conducted using the MTS-816 type rock servo gas solid coupling test system. The test samples are obtained from the six-coal 11316 working face of the Xie Qiao coal mine, Huainan. The sample is processed into a standard cylinder of  $\phi 50 \text{ mm} \times 100 \text{ mm}$  according to international standard requirements, as shown in Fig. 5 and 6.



Fig. 5. MTS-816 test



Fig. 6. Standard coal samples

## 4 Result Analysis and Discussion

A mechanical test with initial gas pressures of 0, 1, 2, and 3 MPa is conducted based on the fracture propagation law of coal mining and instantaneous energy evolution theory of dilatation.

### 4.1 Destructive morphology analysis of coal containing gas

The fractured form of coal containing gas under different gas pressures is shown in Fig. 7. A considerable difference in the damage form of coal containing gas loading is apparent under different gas pressures. The failure of unadsorbed gas coal sample is mainly caused by crack expansion or a large block form, as shown in Fig. 7(a), thereby demonstrating typical shear failure. The breaking degree of the coal containing gas is intense and the diameter of the damaged block is small with increased gas pressure. The main loading

failure consists primarily of small fragments when the original gas pressure of gas coal is 3 Mpa, as shown in Fig. 7(d). This finding shows that gas exacerbated the extent of coal burst cracking, which manifested as changes in the mechanical properties of coal.

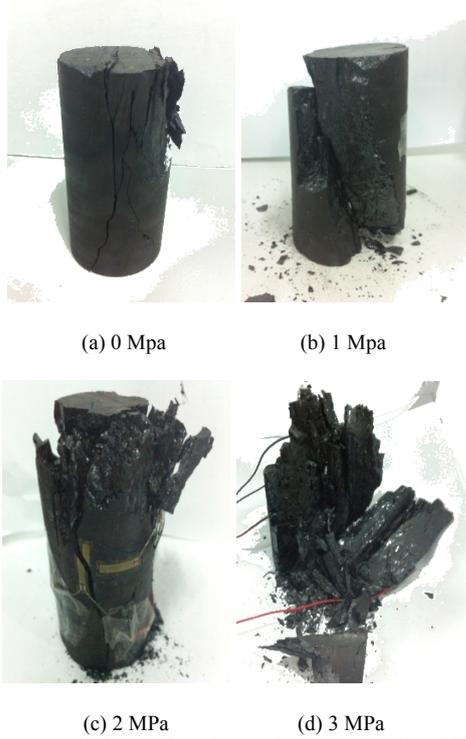


Fig. 7. Fractured form of coal containing gas under different gas pressures

**4.2 Analysis of energy evolution during the dilatancy stage of coal containing gas**

The curves of stress–axial strain–volume strain and strain–gas pressure of coal containing gas are shown in Fig.8 and 9, and the mechanical characteristic parameters are shown in Tab. 1.

**Table 1.** Mechanical parameters of gassy coal dilatancy

Gas pressure (MPa)	$\sigma_k$ (MPa)	$\Delta P/\Delta \epsilon$	$\sigma_c$ (MPa)	Elastic modulus (GPa)
0	11.2	-	17.3	4.12
1	6.8	-0.83	15.1	3.49
2	6.0	-1.01	13.9	3.35
3	5.5	-3.01	11.9	2.93

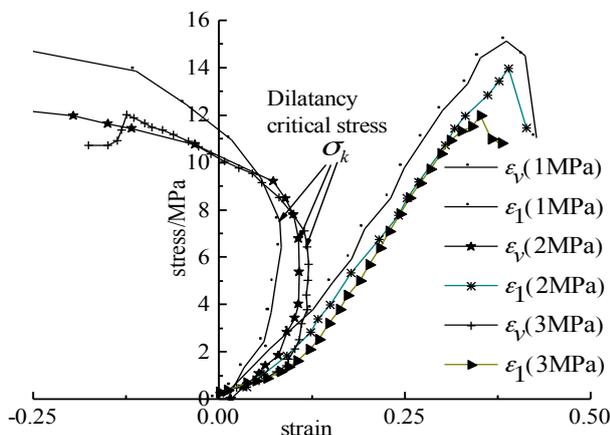


Fig. 8. Stress–strain curve of gassy coal

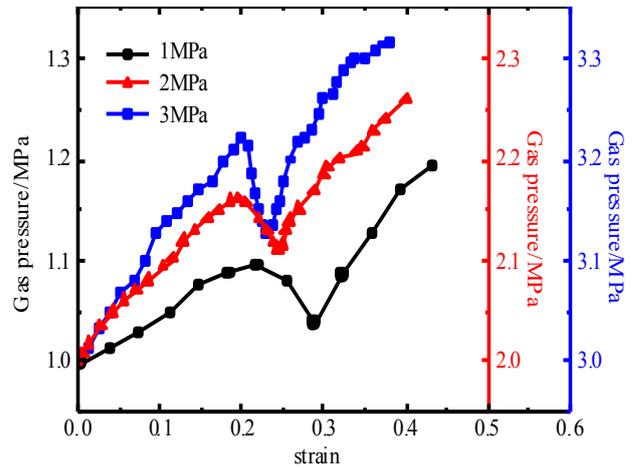


Fig. 9. Change curve of gas pressure with gassy coal dilatancy

The analyses of Tab.1 and Fig.8 show that the gas pressure exhibits a significant influence on the mechanical behavior of the dilatancy of coal rocks. The critical stress value of coal containing gas decreases with the increase in gas pressure. When the initial gas pressure is 0 MPa, the dilatancy critical stress value is 11.2 MPa. When the initial gas pressure increases to 1 MPa, the critical value of dilatancy decreases to 6.8 MPa, demonstrating a drop of 39%. When the initial gas pressure increases to 3 MPa, the critical value of dilatancy decreases to 5.5 MPa, exhibiting a drop of 51%. The increase in initial gas pressure results in greater reduction in critical stress.

The mechanical characteristics of coal containing gas change significantly under different initial gas pressures. When the initial gas pressure increases from 0 Mpa to 3 MPa, the elastic modulus of coal containing gas decreases from 4.12 GPa to 2.93 GPa, compressive strength decreases from 17.3 MPa to 11.9 MPa, and critical stress of dilatation decreases from 11.2 Mpa to 5.5 Mpa. With the increase in initial gas pressure, the decreasing extent of elastic modulus and compressive strength of gassy coal increases, the gassy coal weakens the capability of deformation and failure and is prone to dilatancy. Tab.1 and Fig. 9 show that the gassy coal with different initial gas pressures (1, 2, and 3 MPa) abruptly increases after the gas pressure in the dilatancy phase first decreases and then changes suddenly. The initial gas pressure significantly influences the change in gas pressure during the dilatancy stage. When the initial gas pressure is 1 MPa, the pressure gradient of gas mutation is -0.83. When the initial gas pressure is 3 MPa, the pressure gradient of gas mutation is -3.01, thereby indicating an increase of 264% compared with the initial gas pressure of 1 MPa. The gas pressure gradient in the stage of dilatancy is significantly increased with increasing initial gas pressure.

Under the same mining stress, the dilatancy critical stress of gassy coal seam decreases, and the mechanical behavior of dilatancy easily occurs with the increase in gas pressure. The increase in gas pressure gradient during the dilatancy of gassy coal seam increases the energy of gas expansion. The ability to resist deformation and destruction of the gassy coal seam is weakened, the energy required for destabilization and destruction is greatly reduced, and coal and gas outburst dynamic disaster is easily induced with the increase in gas pressure.

### 4.3 Analysis of the disaster criterion of dilatancy of coal containing gas

The combined test results show that the elastic deformation energy of gassy coal seam, expansion energy of dilatancy and dissipation energy for coal fracture propagation, and dilatancy of coal containing gas-induced disaster index can be calculated with different gas pressures according to Equation (5), as shown in Tab. 2.

**Table 2.** Energy composition and safety evaluation index of gassy coal dilatancy process

Gas pressure (MPa)	$W_e$ (J)	$W_p$ (J)	$W_k$ (J)	$W_e/(W_e+W_p)$ (%)	$R_k$
1.0	26.94	1378.19	31.64	54.01	0.04
2.0	23.28	1306.47	99.15	80.99	0.09
3.0	14.87	245.67	300.88	95.29	1.29

Tab. 2 shows that when the initial gas pressure increases from 1 MPa to 3 MPa, the elastic deformation energy of coal containing gas can be reduced from 26.94 J to 14.87 J. The expansion energy of gas dilatancy increases from 31.64 J to 300.88 J, and the dissipated energy required for crack propagation in coal dilatancy is reduced from 1378.19 J to 245.67 J. The stored elastic deformation energy and energy dissipation of fracture expansion of gassy coal gradually decrease, while gas expansion energy increases rapidly with the increase in initial gas pressure. The safety evaluation index of disaster caused by dilatancy increases with the increase in gas pressure but does not linearly increase. When the initial gas pressure increases from 2 MPa to 3 MPa, the safety evaluation index of disaster caused by dilatancy increases from 0.09 to 1.29, indicating that the initial gas pressure is 3 MPa. The occurrence of dynamic disaster can only be caused by the influence of mining.

In sum, the coal seam gas pressure increases, and the coal seam is prone to dilatancy due to high mining stress. The dissipation energy of coal failure decreases with increased initial gas pressure. The increase in the gradient of gas pressure variation is caused by coal dilatancy, thereby increasing the expansion energy of gas released during dilatancy considerably, which can easily induce coal and gas dynamic disasters.

## 5. Conclusions

The mechanism of dilatancy caused by coal crack is analyzed based on the physical mechanical characteristics of gassy coal to explore the mechanism of coal and gas dynamic disaster induced by coal dilatancy in the working face. The mechanism and criteria of dilatancy-induced disaster of coal containing gas are studied according to the energy evolution characteristics of coal face during the dilatancy stage. The following conclusions are obtained in this study:

(1) The heterogeneity of coal face and the action of high differential stress are the basic causes of the nonlinear growth of cracks in coal. The fractures in the coal mass show nonlinear growth, which easily induces dilatancy. The dilatancy of the coal face depends on the force environment and the physical and mechanical properties of the coal.

(2) The gas pressure of the coal rocks increases with increased mining stress, reducing the critical stress of the coal dilatancy and causing the mechanical phenomenon of dilatancy to occur easily. With the increase in gas pressure, the change gradient of gas pressure increases, the coal rocks are enlarged, and the gas expansion energy is greatly increased during dilatancy. The ability of coal body to resist deformation and damage is reduced. As a result, dynamic disaster can be induced easily.

(3) An energy criterion model of dilatancy-induced disaster of coal containing gas is established on the basis of the principle of energy conservation. A dynamic disaster occurs when the gassy coal storage energy increases more than the energy required for dilatancy and instability. Dynamic disaster does not occur when the gassy coal storage energy is less than the energy required for its destruction and dissipation.

The proposed energy dissipation model of dilatancy-induced disaster of coal containing gas has a clear concept and a simple form, with easy-to-determine energy parameters and is easy to determine in real time. The proposed model can also predict the occurrence of coal and gas dynamic disasters scientifically. However, the coal-gas dynamic desorption process occurs with the instantaneous dilatancy of gassy coal, thereby changing its physical and mechanical properties, which may lead to the containment of gassy coal storage elastic properties and gas expansion energy parameters set with the actual existence of a certain deviation. Therefore, in the future, further studies should be conducted on the desorption and adsorption laws of gas during the dilatancy of coal containing gas, fully considering the influence of gas desorption of gassy coal on energy parameters to improve the scientific capability of the criterion model. This study provides a new theoretical basis for understanding the mechanism of gas dynamic disaster in coal seams.

## Acknowledgements

This study was supported by the Natural science research project of University of Anhui Province (NO. KJ2015A048, KJ2017A093), the National Natural Science Foundation of China (NO. 51774014).

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence



## References

- Xue, S., Yuan, L., J. Xie., Wang, Y. C., "Advances in gas content based on outburst control technology in Huainan, China" . *International Journal of Mining Science and Technology*, 24(3) , 2014, pp.385-389.
- HE, M. CH., XIE, H. P., PENG, S. P., JIANG, Y. D., "Study on Rock Mechanics in Deep Mining Engineering". *Chinese Journal of Rock Mechanics and Engineering*, (16) , 2005, pp. 2803-2813.
- XIE, G. X., HU, Z. X., WANG, L., "Coal mining dilatancy characteristics of high gas working face in the deep mine". *Journal of China Coal Society*, 39(1), 2014, pp.91-96.
- Beamish, B., Basil, Crosdale., Peter, J., "Instantaneous outbursts in underground coal overview and association with coal type". *International Journal of Coal Geology*, 35, 1998, pp.27-55.

5. Hu, Y.Y., Hu, X. M., Zhang, Q.T., "Analysis on simulation experiment of outburst in uncovering coal seam in cross-cut", *Procedia Engineering*, 45, 2012, pp. 287-293.
6. Díaz, Aguado, María, B., González Nicieza, C. "Control and prevention of gas outbursts in coal mines, Riosa-Olloniego coalfield, Spain", *International Journal of Coal Geology*, 69, 2007, pp.253-266.
7. Agi, B., Joan, S. E., Suzanne, D. G., "Horizontal stress anisotropy and effective stress as regulator of coal seam gas zonation in the Sydney Basin", *International Journal of Coal Geology*, 132, 2014, pp. 103-116.
8. Bridgman, P.W., "Volume changes in the plastic stages of simple compression". *JAppl Phys*, 20, 1949, pp. 1241-1251.
9. Matsushima, S., "On the flow and fracture of igneous rocks and on the deformation and fracture of granite under high confining pressure". Kyoto, Disaster Prevention Res Inst Kyoto Bull, 1960.
10. Handin, J., Hager, R. V., Friedman, M., "Experimental deformation of sedimentary". *Zeitschr. Ver. Deutsch*, 20, 1960, pp. 1241-1251.
11. Haimson, B., "A new true triaxial cell for testing mechanical properties of rock, and its use to determine rock strength and deformability of Westerly granite". *Int J Rock Mech Min Sci*, 37, 2000, pp. 285-296.
12. Alejano, L.R., Alonso, E., "Considerations of the dilatancy angle in rocks and rock masses". *International Journal of Rock Mechanics and Mining Sciences*, 42(4), 2005, pp. 481-507.
13. Chen, Z. J., Wen, X. M., "Swelling Rocks And Stability of Tunnels". *Chinese Journal of Rock Mechanics and Engineering*, 2(1), 1983, pp.1-10.
14. Cao, Sh. G., Xian, X. F., "Damage Analysis on Coal and Rocks and the Method of the Checking Damage by the Deviator Stress". *Journal of Chongqing University(Natural Science Edition)*, 24 (4), 2001, pp.75-77.
15. Pan, L.Y., Zhang, W. G., Yang, H. Zh., "Experimental Research on Volume-expanding Properties of Impact Coal-mass". *Journal of Shandong Inst.of Min.& Tech*, 24(1), 2005, pp.18-20.
16. Hu, Z. X., Xie, G. X., "A research of asynchronous and synchronous characteristics of coal seam gas pressure controlled by the mining-induced stress". *Journal of Mining & Safety Engineering*, 32(6), 2015, pp.1037-1042.
17. Kidybinski, A., "Bursting liability indices of coal", *International Journal of Rock Mechanics and Mining Sciences*, 18(6), 1981, pp.295-304.
18. Aksoy, C. O., Ozacar, V., Yilmaz, A., "New laboratory equipment for rock breakability classification with impact energy", *International Journal of Rock Mechanics and Mining Sciences*, 54, 2012, pp.159-164.
19. Zhang, J.C., Xu, W.Y., Wang, H. L., "A coupled elastoplastic damage model for brittle rocks and its application in modelling underground excavation", *International Journal of Rock Mechanics and Mining Sciences*, 84, 2016, pp.130-141.
20. Zhang, Z. Z., G, F., "Experimental investigations on energy evolution characteristics of coal, sandstone and granite during loading process". *Journal of China University of Mining & Technology*, 44(3), 2015, pp.416-422.
21. Goodman, R. E., "Introduction to rock mechanics". New York: John Wiley and Sons, 1980.
22. Liang, Ch. Y., Li, X., W, Sh. X., "Experimental Investigations on Rate-Dependent Stress-strain Characteristics and Energy Mechanism of Rock under Uniaxial Compression", *Chinese Journal of Rock Mechanics and Engineering*, 31(9), 2012, pp.1830-1838.
23. Kavan, K., Elham, M., Maria, D., "Stability and serviceability of underground energy storage caverns in rock salt subjected to mechanical cyclic loading", *International Journal of Rock Mechanics and Mining Sciences*, 86, 2016, pp.115-131.
24. Xie, H. P., Ju, Y., Li, L. Y., "Energy mechanism of deformation and failure of rock masses", *Chinese Journal of Rock Mechanics and Engineering*, 27(9), 2008, pp.1729-1740.
25. Li, T. B., Chen, Z. Q., Chen, G. Q., "An experimental study of energy mechanism of sandstone with different moisture contents", *Rock and Soil Mechanics*, 36(S2), 2015, pp.229-236.