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Analysis of coal crack and permeability characteristics slotted by water jet and the effect on gas outburst

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ABSTRACT
Water jet slotting technology is an effective method of increasing coal permeability, improving gas extraction quantity, and preventing mine gas dynamic disasters. The designs of the slot parameter and layout are the key factors. The present study investigated the mechanical properties of slot samples and acoustic emission characteristics in different slotting numbers and angles by uniaxial loading tests. Tests indicated that the coal strength was weakened by slotting and reduced significantly with increasing slotting numbers, and the coal was damaged more easily when the slot plane was perpendicular to the axial stress. Using Guhanshan coal mine 1603 working face as an example, the paper analyzed the evolution of the coal fracture, stress and porosity when the slots were at the same level and at the different levels by numerical simulation of Particle Flow PFC2D. The results showed that, to the sample of slots at the same level, the area around the slot was damaged significantly and the stress concentration was distributed between the adjacent slots, which easily induced coal and gas dynamic risk. However, the stress and crack fields were distributed uniformly when the slots were at the different levels, the stress was decreased significantly, and the porosity of coal was 1.5 times higher than the original value.
KEYWORDS: Mine safety; gas extraction; permeability improve; hydraulic cutting; slot layout

1. INTRODUCTION

Underground coal seam hydraulic technology, such as water jet slotting technology and hydraulic fracturing technology, can effectively increase the coal permeability, (Huang et al., 2011). The influence of hydraulic fracturing technology is large, but the fractures improving permeability are easily closed again when the coal is soft and the geostress is high. However, water jet cutting forms large-sized slots and fractures, which can reduce the geostress level and expand the coal cracks (Shen et al., 2012). It is an effective method to prevent outburst occurrence and improve gas extraction. Research on the improvement of of coal permeability by water jet cutting has been done. Based on the rock dynamic damage model, Li and Lu analyzed and numerically simulated coal dynamic damage and fracture impacted by the high-pressure pulse water jet, and considered that the pulse function significantly affected the state of coal fracture field (Li et al., 2000; Lu et al., 2010). Lu (Lu et al., 2009; Lu et al., 2011) considered that water jet cutting technology can release the internal energy and reduce the coal seam stress level, which improves the gas drainage volume and eliminates the outburst risk. However, the permeability influence on the coal damage induced by the slots isn't negligible, especially multi-level slotting. Therefore, the authors have carried out research on the coal permeability improvement mechanism of the slot crack network by water jet multi-level slotting, in order to improve CMG extraction. The study took Guhanshan Coalmine as the background, and using acoustic emission (AE) technology analyzed the multi-level slotting coal mechanical properties and crack propagation characteristics under the condition of uniaxial loading. Then, using PFC2D the fracture was numerically simulated as well as stress and porosity evolutions of the slotting coal. The study results are of great significance for the improvement of Chinese CMG extraction underground.

2. CRACK PROPAGATION EXPERIMENT

2.1 Experiment system

The experiment system mainly includes the MTS servo machine, AE instrument, and video camera. When slotting the coal under the uniaxial loading, AE was monitoring the crack extension and at the same time the camera was monitoring the deformation and the failure of the sample surface (Figure 1). The type of MTS was C64.106, of which the rated load was 1000 kN and the displacement resolution was 0.2 μm. The AE system with 8 channels was produced by PAC company, of which the center resonance frequency was 120 kHz, the pre-amplifier and main

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amplifier gain were 40 dB, and the adjusting threshold voltage was 1.0 V.

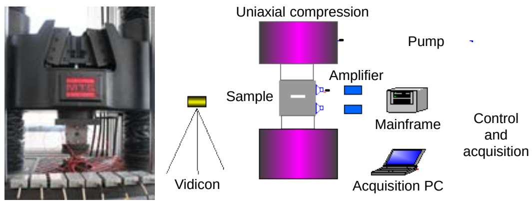


Figure 1: Experiment system schematic of uniaxial compression.

2.2 Sample preparation

Using similar materials the side length of 100 mm cubic coal samples with no slot and with three slots were prepared. The slot width was 20 mm, the thickness was 2.5 mm, and the angle of the slot surface and horizontal plane was 0°. The raw materials of the samples were pulverized coal (grain diameter of 0.2-1.0 mm), cement, gypsum powder and water and mixed into the mold. The samples were maintained 45 days to form and the slots were formed through pre-embed metal bars. In order to compare the sample mechanics performance with the original coal, firstly, large pieces of original coal from Guhanshan Coalmine 1063 working face were collected, then processed into the standard specimens in the laboratory. Lastly, the mechanics parameter of the similar material and the original coal samples were tested. As Table 1 shows, the mechanics parameters were similar.

Table 1: Mechanics parameters of coal and similar material samples.

Sample	Compressive strength σ_c/MPa	Elasticity modulus E/GPa	Tensile strength σ_t/MPa	Shear strength τ/MPa
raw coal	5.60	0.78705	0.72	3.03
similar material	6.24	0.954	0.87	4.28

2.3 Text operation

Each type of sample test was repeated three times, and the test parameters and conditions were as follows: ① select MTS loading mode and set the stress loading rate as 1.0 kN/s, when the sample damaged, stop loading, ② eight sensors of AE are evenly placed on the four free surfaces, and each surface has two pieces. Before testing, set up and debug the instrument, and paste the sensor on the sample surface. Then, contact the MTS pressure plate with the sample by a small load, and then start the MTS loading system, the AE instrument, and the camera. When the loading up to the sample is damaged, stop the test and collect the features of the broken sample.

3. RESULTS ANS ANALYSIS

3.1 Slot coal mechanical strength

The different slot angle and slot number of peak stress block statistics are shown in Figure 2. The peak stress of the single slot sample was the largest, and as slot angle increases, the peak stress increases. When the slot angle was 0° to 45°, peak stress increased obviously. The slot number increased and peak stress was decreased. Compared to the single slot sample, the peak stress of the double slot and three slot samples were decreased by 30-50%. Based on the test results, slotting could change rock mechanics properties, where when slot number increases the coal compressive strength is decreased. When the slot number reaches a certain amount, there is less of an effect on the coal rock mass mechanics performance. For single slot samples, when the slot plane and the maximum principal stress were vertical, the sample failed easily.

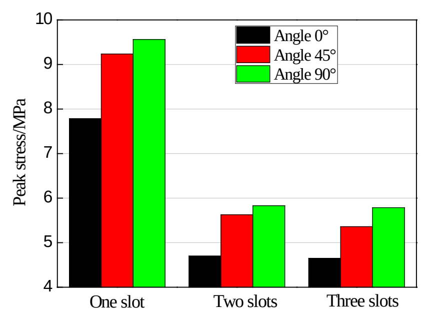


Figure 2: Peak stress distributions of different slotted samples.

3.2 Crack propagation of AE features

The peak stress of three slots sample with two levels distributed was far less than that of the no slot sample (Figure 3). AE parameters were very small in the initial compaction stage and elastic deformation stage, increased in the plastic deformation stage, and increased significantly when approaching the peak stress. In the yield strain stage, the value of AE energy and accumulated events increased markedly, the number of AE hits maintained a high rate and slowly decreased, which shows that the crack propagated easily. The locations of AE events were as shown in Figure 4. The cracks between the slots surfaces grew early on. At 60% of peak stress, the cracks distributed between the slots above and below were concentrated and at the same time, the cracks around the slot expanded to the boundary. At the peak stress, a lot of cracks around the slots grew quickly.

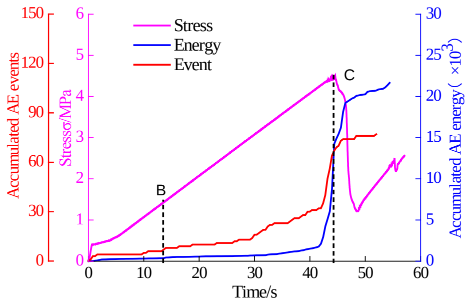
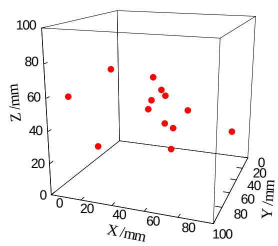
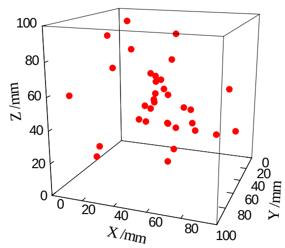


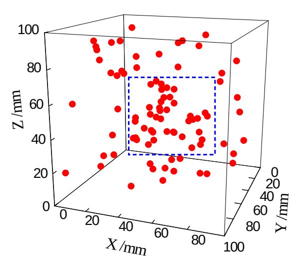
Figure 3: AE parameter variation of three slots sample with two level distributed.



(a) 20% peak stress



(b) 60% peak stress



(c) Peak stress

Figure 4: AE events locating process of three slots sample with two level distributed.

4. CRACK EVOLUTION PFC SIMULATION

4.1 Numerical model

Using particle flow PFC2D to build a rectangular model with the incompetent bed (Cundall, 2004), the model length as 1400 mm and the width was 900 mm. The model was divided into three stratums, including the roof rock stratum (200 mm), incompetent bed (500 mm), and bottom rock stratum (200 mm), the original particle model was as shown in Figure 5. The parameters of the roof and floor rocks were the same, the bond strength of which was five times more than the incompetent bed, as shown in Table 2. The parallel bond parameters were as shown in Table 3. In order to simulate the confining stress limiting conditions, the limit wall was set all around the model, and four walls would load in the calculation. To simulate and analyze the effect of different slot fracture size and distribution, two slot models were established by deleting particles from the incompetent bed. The parameters and distributions of the slot fractures were as shown in Figure 6. The slot distribution was heterogeneous. The particle parameters between the surfaces and on both ends of the slots were recorded in the processing of the simulation, shown as the circles in Figure 6.

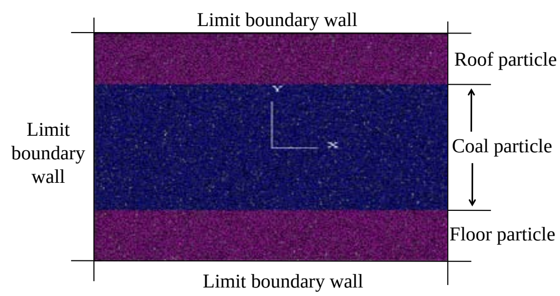


Figure 5: Particle model including boundary and particles stratum.

Table 2: Basic parameters of the model.

Parameter name	value
Minimum grain diameter (mm)	0.3
Particle diameter ratio	1.66
Particle density (kg/m^3)	1450.0
The ball - the ball contact modulus (GPa)	0.8
Particle stiffness ratio	1.0
Friction coefficient between particles	0.5

Table 3: Parallel bond parameters.

Parameter name	value
Parallel bond radius multiplier	1.0
Parallel bond modulus (GPa)	0.8
Normal stress average value of parallel bonding (MPa)	4
Normal stress standard deviation of parallel bonding (MPa)	0.01
Tangential stress average value of parallel bonding (MPa)	4
Tangential stress standard deviation of parallel bonding (MPa)	0.01

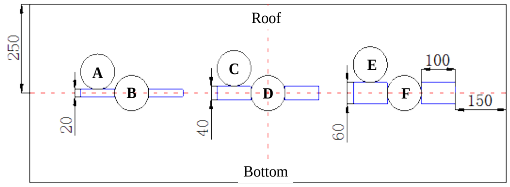
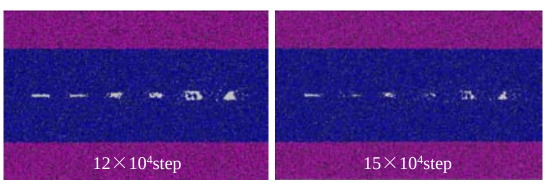


Figure 6: Slot fractures model parameters and distributions.

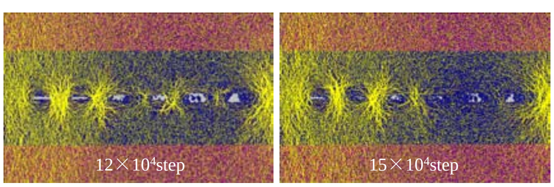
4.2 Simulation results and discussion

The single-level slots rock model structure, stress and crack distribution are shown in Figure 7. With the load step increasing, the deformation displacement around big slot happened first, and the slots were filled with particles. Stress appeared around the small and medium-sized slots, and the stress concentration appeared between the adjacent slots. As the calculating steps increased, the stress around large slot and medium slot area were reduced. With the stress increasing, crack propagation around the big slot was not significant, and mainly took the form of tension fractures. However, the cracks around the secondary slot increased mainly due to shear failure, and the crack around the small slot grew and expanded to the roof and floor.



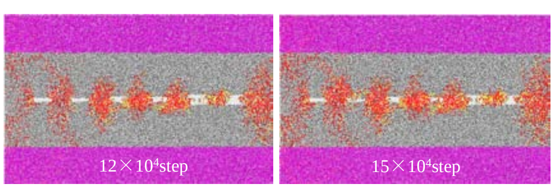
Rock stratum of roof and floor   incompetent bed   Slot

(a) Particle structure change



Compressive stress   Tensile stress   Slot

(b) Model stress distribution



Shear failure   Tensile failure   Roof and floor   incompetent bed   Sl

(c) Crack evolution and distribution

Figure 7: Crack evolution of single -level slots model in loading.

The instantaneous stress, porosity and coordination number and particle migration around the small slots in the unit circle A and B were as shown in Figure 8. The stress of A position showed continuous increase, lower porosity, and coordination number increase. The stress of location fluctuated and increased to about 12 MPa. The porosity increased after the first reduction, but remained lower than the original. The instantaneous stress, porosity and coordination number and particle migration around the medium slot in the unit circle C and D were as shown in Figure 9. The stress of C position increased slowly and the porosity declined. The stress of D location increased to about 10 MPa first, and then reduced to 2 MPa. The porosity significantly increased to far more than the original porosity at the first peak stress. The instantaneous stress, porosity and coordination number and particle migration around the large slot in the unit circle E and F were as shown in Figure 10. The stress of E position slowly increased, the maximum of which was lower than the small and medium slots. The porosity was similar to the original, however, the coordination number and particle instantaneous displacement were not obviously changed. The stress of F position was irregular. In the first peak stress, the porosity increased rapidly and then increased slowly. The porosity increased to about 1.5 times higher than original value.

Stress   Porosity   Coordination   Migration

Figure 8 : Parameter variation around the small slots (B location).

Stress   Porosity   Coordination   Migration

Figure 9 : Parameter variation around the medium slots (D location) .

Figure 10: Parameter variation around the large slots (F location).

The analysis above found that the greater the slot width, the lower the rock peak stress around the slot, and the rock mass was more easily broken. Due to the low stress, the porosity was increased significantly. The cracks were mainly distributed around the area of the adjacent slots. Compared with the multi-level slots model, the cracks and stress were unevenly distributed, inducing the instability phenomenon.

5. CONCLUSIONS

(1) The experiment found that multi-level slots can significantly weaken the coal strength, cause the occurrence of micro-cracks around the slot, cause crack propagation to form a rock-bridge, and lead to the appearance and extension of numerous micro-cracks around slot surface.

(2) Under the conditions of the same slot arrangement, the peak stress of the big slots model was smaller and the fracture distribution was uneven. As the slot size increased, the rock model became more unstable and the porosity increased significantly after the peak stress. The fractures of the uneven slot distribution model grew and extended more significantly than the even distribution model, and induced the coal and gas to more easily lose stability.

6. ACKNOWLEDGEMENTS

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