Particle flow simulation study on uniaxial compression of coal sample with prefabricated fracture

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Abstract. In view of the actual problems that the cracks and joints of the primary coal body are developed in the coal mine, and the primary cracks have a significant impact on the mechanical properties of the coal body in the process of instability and failure, based on the macro and micro parameters of the coal body, a numerical model of the coal sample with different parameters of the prefabricated cracks is constructed. This paper explores the influence of prefabricated cracks on the mechanical properties of coal samples, analyzes the specific role of prefabricated cracks on the peak strength and crack propagation of coal samples in the failure process of coal samples, and reveals that the prefabricated cracks have an important influence on the support strength and meso characteristics of coal samples in the process of uniaxial compression. It provides ideas and basis for predicting the support strength of coal body and strengthening the support mode and parameters in the fracture development area of coal mine.

Keywords: Prefabricated crack; Uniaxial compression; Crack propagation; particle flow code

1. Introduction

Coal and rock mass in nature contains various defects, such as pores, cracks, joints, etc. These defects will seriously affect the mechanical characteristics and failure characteristics of coal and rock mass. According to the test results of relevant literature, the uniaxial mechanical strength of different coals is quite different. For hard coals with complete structure, the uniaxial compressive strength can exceed 10MPa, while for coal with developed joints or structural coals, the uniaxial compressive strength can be less than 3 MPa [1]; However, the primary cracks in coal rock have obvious influence on the mechanical characteristics and failure modes of coal, and many scholars have carried out relevant research. For example, Guo Jingyu et al. [2] carried out static to quasi-static uniaxial compression tests at different loading rates on rock-like materials containing 0.1mm prefabricated fractures, and analyzed the breaking law of rock-like materials in fractured bodies under the combined influence of loading rate and fracture dip angle; Cheng Aiping [3] et al. carried out uniaxial compression test on cemented backfill with lime-sand ratio of 1:4, and obtained the conclusion that the crack propagation and convergence mode of cemented backfill is mainly single crack unidirectional propagation and single crack bidirectional propagation, and there is symmetry and adjacency between surface penetrating cracks;
Zhang Liang et al. [4] studied the evolution law of energy index in the process of deformation and failure of single fractured rock mass under uniaxial compression, and divided the energy damage of fractured rock mass into six stages: initial damage stage, stable damage stage, stable damage stage, abrupt damage stage, accelerated damage stage and damage and failure stage, fitting the relationship between energy change and fracture length in each stage; Li Dexing et al. [5-8] conducted corresponding tests on compression failure of cracked coal samples from macroscopic crack dip angle, acoustic emission response, localization characteristics and failure mode, and described the influencing factors and macroscopic response characteristics in detail.

To sum up, the existence of cracks will have a significant impact on the mechanical properties of coal and rock samples. However, due to the impact of coal strength and brittleness, prefabricated cracks in the laboratory can easily cause the overall damage of coal samples or produce microscopic damage invisible to the naked eye, thus affecting the accuracy of experimental results. Therefore, there is no relevant experimental study on prefabricated cracks in coal samples at present. With the development of numerical test technology, a large number of researches have been carried out to analyze the mechanical behavior of coal under uniaxial compression by particle flow method, but the influence of prefabricated cracks on the overall mechanical properties of coal seam has not been considered. Based on the research results of related scholars, the author uses PFC\textsuperscript{2D} software to establish coal sample models with different prefabricated fractures, and simulates the uniaxial compression particle flow of coal samples with prefabricated fractures. Tracing the propagation and penetration process of cracks around prefabricated cracks and the number of types of shear cracks and tension cracks, the distribution of internal particle displacement field and fracture development process of cracked samples after loading are analyzed from the microscopic point of view, and the uniaxial compression model test of coal under the coupling action of cracked coal samples and different loading modes is established, so as to provide reference for field application.

### 2. Construction of numerical model of coal samples with prefabricated cracks

#### 2.1. Determination of coal macro and meso parameters

Coal samples were taken from Yingcheng Coal Mine of Yingcheng Mining Co., Ltd., Jilin Province, and all samples were taken from the same coal seam and the same place. After uniaxial compression and Brazilian splitting tests on coal samples in laboratory, macroscopic mechanical parameters such as elastic modulus, Poisson's ratio, uniaxial compressive strength and tensile strength of primary coal are obtained. Meanwhile, the relationship between macroscopic and microscopic parameters is obtained by fitting several sets of numerical simulation tests. The meso-parameters of native coal body are shown in the following table.

| Table 1 Micro mechanical parameters of uniaxial compression tests of hard coal |
|---------------------------------|---------------------------------|
| **Mesoscopic parameters of parallel bonding** | **Mesoscopic parameters of particle contact** |
| $\overline{E^*/GPa}$ Bond modulus | $R_{max/mm}$ Maximum particle radius 0.50 |
| $k_n/k_s$ Bond stiffness ratio | $E^*/GPa$ Contact elastic modulus 5.13 |
| $\overline{\sigma_c}/MPa$ Bond strength | $Kn/ks$ Contact stiffness ratio 2.10 |
| $\overline{c}/MPa$ Cohesive cohesion | $f$ Coefficient of contact friction 0.70 |
| $\overline{\phi}/(\degree)$ Bond internal friction angle | $\text{Poros}$ Porosity 0.12 |
2.2. Geometric parameters of prefabricated cracks

A great deal of research has been done on the pore characteristics of coal and rock mass by predecessors, and the pores of coal and rock media are divided into three types: pore, micro-fracture and macro-fracture [9]. Pores and micro-cracks belong to micro-morphology, while macro-cracks are cracks that can be directly observed by naked eyes. The width of cracks is generally larger than 0.1 mm. According to the size, characteristics and causes of cracks, they can be divided into micro-cracks, small cracks, medium cracks and large cracks, with lengths ranging from several centimeters to hundreds of meters. According to the actual situation that the geometric dimensions of the test specimen are 100mm high and 50mm in diameter, the geometric dimensions of prefabricated cracks are determined as rectangular regular cracks with a length of 15mm and a width of 1mm, and the inclination angles of prefabricated cracks are 0°, 15°, 30°, 45°, 60°, 75° and 90° respectively.

3. Numerical test results

3.1. Influence of inclination angle of prefabricated crack on peak strength

It can be seen from the test results that the fracture dip angle has a great influence on the peak stress of coal samples under uniaxial compression. According to the gradient of 15°, we gradually increase the dip angle of prefabricated cracks, from 0° in horizontal direction to 90° in vertical direction. From the test results, it can be seen that the peak stress decreases first and then increases. The peak stresses at 0° to 90° dip angles are 4.5MPa, 4.2MPa, 4.53MPa, 5.0MPa, 5.1MPa, 5.48MPa and 6.9MPa, respectively. The minimum peak stress occurs when the pre-fabricated fissure dip angle is 15°, while the maximum peak stress occurs when the fissure dip angle is 90°.

Due to the various changes of coal seam cracks in coal mines, the cracks are simplified as rectangular cracks with uniform width in numerical experiments. According to the changes of stress curves under various dip angles, the following conclusions can be drawn: 1) With the increase of fracture dip angle, the peak stress of uniaxial compression first decreases and then increases, and the fracture dip angle corresponding to the minimum peak stress is 15, which indicates that the prefabricated fracture with 15 dip angle has the greatest degradation degree to coal samples, while the prefabricated fracture with 90 dip angle has the smallest degradation degree to coal samples. 2) With the increase of fracture dip angle, the ductility and brittleness of coal samples increase gradually, but the brittleness shows a trend of increasing gradually after the peak.

![Fig.1 Axial stress curves of different precast crack dip angles](image-url)
3.2. Influence of inclination angle of prefabricated crack on crack propagation

It can be seen from the figure that under uniaxial compression, the specimen mainly undergoes the following process from internal crack to overall instability failure: Crack initiation stage, which mainly includes local point cracks at the tip or middle of prefabricated cracks. When the angle of prefabricated cracks is small (0° ~ 30°), the probability of crack initiation at the tip and middle of prefabricated cracks is higher. Firstly, point initiation cracks appear. When the angle of prefabricated cracks gradually increases (45° ~ 75°), the areas where point-like cracks first appear are all at the tip of prefabricated cracks. When the angle of prefabricated crack is 90°, it can be seen that prefabricated crack has little effect on the crack initiation position, and the crack initiation position mainly appears at the bottom and middle of the specimen.

Crack propagation stage: With the increase of the number of initiated point cracks, the point cracks gradually expand and converge, and develop from point to linear. When the angle of prefabricated cracks is less than 45° (0° ~ 45°), the expansion direction forms an angle of 90° with prefabricated cracks. When the angle of prefabricated cracks is greater than 45° (60° ~ 90°), the angle between crack expansion direction and prefabricated cracks gradually increases.

Crack penetration stage: With the increase of axial stress, with the emergence of new cracks in different areas, a number of scattered cracks gradually appear to connect with each other, forming a through-type main crack, spreading and branching along the main crack, and deriving more secondary cracks.

![Crack Occurrence](image)
Crack initiation   Crack propagation (Inclination angle is 0°)   Crack penetration   Failure form

Crack initiation   Crack propagation (Inclination angle is 0°)   Crack penetration   Failure form

Crack initiation   Crack propagation (Inclination angle is 0°)   Crack penetration   Failure form

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Crack initiation   Crack propagation (Inclination angle is 0°)   Crack penetration   Failure form
Crack initiation  Crack propagation (Inclination angle is 0°)  Crack penetration  Failure form

Fig.3 The failure mode of coal samples with different prefabricated cracks

According to Zhang Xiaoping's research [10-11], under uniaxial compression, the crack propagation at the crack tip of rock-like material can be divided into airfoil crack, anti-airfoil crack and secondary crack. The airfoil crack is tension crack, which starts at the crack tip at a certain angle with the prefabricated crack and develops towards the maximum principal stress. Anti-airfoil crack is a crack which develops in the opposite direction to airfoil crack, and secondary crack is a shear crack which originates from crack tip.

Fig.4 The classification of failure cracks in coal samples
It can be seen from the comparison of failure forms of prefabricated cracks with various dip angles in the figure that when the dip angles of prefabricated cracks are 0°, 15° and 30°, the final failure crack form is reverse airfoil crack; When the inclination angle of prefabricated cracks increases to 45°, 60° and 75°, the final failure crack form is airfoil crack; However, when the inclination angle of prefabricated crack continues to increase to 90°, the final failure crack form is that both airfoil and anti-airfoil cracks exist, accompanied by secondary micro-cracks in all directions. According to the research results of Liu Jie et al. [11], the main reason is that there are a large number of defects in coal samples, and the internal stress is randomly distributed and the deformation and failure also occur randomly when compressed. When the prefabricated fractured coal sample is compressed, the stress concentration zone will be formed near the fracture, especially at the fracture tip. The existence of prefabricated cracks makes the internal cracks have a direction of propagation and penetration, which is prone to crack concentration and macro cracks. When the tip of prefabricated crack is mainly under tensile stress, the crack propagation along the inclined direction of prefabricated crack is formed after the tip is destroyed, and the airfoil crack is formed. When the tip of the prefabricated crack is stressed under compression, the crack propagates in the opposite direction along the inclined direction of the prefabricated crack after the tip is damaged, and the anti-wing crack is formed. Therefore, it can be obtained that the compressive stress at the crack tip in the failure process is opposite to that of the prefabricated crack, while the tensile stress at the crack tip in the failure process is the same as that of the prefabricated crack when the prefabricated crack is inclined at a large angle, while the microcrack occurs between the airfoil and the reverse airfoil when the prefabricated crack angle reaches 90° and is parallel to the radial direction of the specimen.

4. Summary
In this paper, the macro and micro mechanical parameters of primary coal are used to construct the numerical model of primary coal standard specimen with prefabricated cracks, and the uniaxial compression numerical simulation test of the numerical model specimen with prefabricated cracks with uniform width and different dip angles is carried out to discuss the influence of different dip angles of prefabricated cracks on the uniaxial compression mechanical properties of coal. The process of crack distribution, propagation and fracture in the specimen under load is analyzed from the microscopic point of view, and the decrease of uniaxial compressive strength and the change of crack propagation mode are shown macroscopically. The main conclusions are as follows:

(1) The results show that the prefabricated cracks have obvious influence on the mechanical properties of coal under uniaxial compression. When the parameters of prefabricated cracks change, the uniaxial compressive strength of coal samples with prefabricated cracks decreases in different degrees, especially when the inclination angle of prefabricated cracks is 15°, the uniaxial compressive strength of coal samples is the smallest, and the prefabricated cracks have the greatest influence on the uniaxial compressive strength.

(2) The influence of precast fissure dip angle on uniaxial compressive strength of coal samples decreases with the increase of fissure dip angle, and the influence of precast fissure on uniaxial compressive strength of coal samples increases gradually when the inclination angle of precast fissure is 0°~15°. The uniaxial compressive strength of coal samples increases gradually when the fracture dip angle ranges from 30° to 90°, while the influence of prefabricated fractures on the uniaxial compressive strength of coal samples decreases gradually.

(3) The inclination angle of prefabricated cracks also has an important influence on the initiation, propagation and ultimate failure mode of cracks in the specimen. When the inclination angle of prefabricated cracks is small, the crack form of reverse airfoil is mainly produced; when the inclination angle of prefabricated cracks is large, the crack form of airfoil is mainly produced; when the inclination angle reaches 90°, the secondary crack is the main failure form.

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References

[1] ZHANG Fei-yan, HAN Ying, YANG Zhilong. An Estimation method of mechanical parameter for soft coal [J]. Safety in Coal Mines, 2013(4): 13-16.

[2] Guo jingyu, he guicheng, Yang Shaofeng et al. Fracture test and acoustic emission characteristics analysis of rock-like materials under combined action of loading rate and fracture dip angle [J]. mining research and development, 2021(1):88-92.

[3] CHENG Aiping, DONG Fusong, ZHANG Yushan, et al. Crack propagation and convergence mode of cemented backfill under uniaxial compression[J]. Journal of China University of mining & Technology, 2021(1): 50-58.

[4] ZHANG Liang, WANG Gui-lin, LEI Rui-de, et al. Energy Damage Evolution Mechanism of Single Jointed Rock Mass with Different Lengths Under Uniaxial Compression[J]. China J. Highw . Transp., 2021(1): 24-34.

[5] LI Dexing, WANG Enyuan, LI Nan, et al. Research on the coal characteristics of macro-crack dip angles under uniaxial compression[J]. Chinese Journal of Rock Mechanics and Engineering, 2017(4):3207-3213.

[6] CHEN Pan, LI Dexing. Numerical simulation research on damage characteristics and acoustic emission response of coal with pre-existing cracks[J]. Industry and Mine Automation, 2018(1):55-63.

[7] ZHANG Tianjun, WANG Xina, JING Chen, et al. Localized deformation characteristics of soft coal with fractures at different dip angles[J]. Journal of xian university of science and technology, 2021(3):203-212.

[8] KANG Xiangtao, LIU Yong, JIANG Chengyu, et al. Influence of water content on energy consumption and destruction form of coal samples with prefabricated crack[J]. China Safety Science Journal, 2017(7):94-98.

[9] XU Honglei. Study on acoustic emission nonlinear dynamic characteristics of pre-cracked coal and rock samples in deformation and failure [D]. 2017(4):18-21.

[10] ZHANG Xiaoping, WANG Sijing, HAN Gengyou, et al. Crack propagation study of rock based on uniaxial compressive test-a case study of schistose rock[J]. Chinese Journal of Rock Mechanics and Engineering. 2011,30(9):1772-1781.

[11] GUO Yanshuang, HUANG Kaizhu, ZHU Weishen, et al. Study on fracture pattern of open surface-flaw in gabbro[J]. Chinese Journal of Rock Mechanics and Engineering. 2007, 26(3): 525-531.

[12] HUANG Da, HUANG Runqiu, ZHANG Yongxing. Experimental investigations on static loading rate effects on mechanical properties and energy mechanism of coarse crystal grain marble under uniaxial compression[J]. Chinese journal of Rock mechanics and engineering. 2012,31(2):245-255.

[13] LUO Ke, ZHAO Guodong, ZENG Jiajun, et al. Fracture experiments and numerical simulation of cracked body in rock-like materials affected by loading rate[J]. Chinese journal of Rock mechanics and engineering. 2018,37(8):1833-1837.