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INFLUENCING FACTORS OF DEFORMATION AND FAILURE OF POROUS COAL UNDER CONVENTIONAL LOADING

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Abstract*. Coal exploration requires draining the gas from the coal seam. For this purpose, drill holes in the coal seam are required. Under the field conditions, the stress and strain states around a drill hole are not easy to determine and the same is valid for the material law defining their dependence. In this study, by arranging boreholes in coal samples, the effects of loading rate, borehole inclination, borehole diameter and other factors that influence the mechanical properties of porous coal are studied. The results show that the strength of porous coal increases with the increase of loading rate, which is consistent with the behavior of non-porous coal. The porous coal samples with certain inclination angles of the drill hole are easier to destroy compared to the porous coal samples with a horizontal drill hole. Furthermore, the failure surface is consistent with the inclination angle, and a specimen with an upward inclination angle of the drill hole is easier to destroy compared to a specimen with a downward inclination angle. Comparing the samples with the borehole diameters of 5 mm and 10 mm, the axial deformation and transverse deformation of the latter are 1.7 times and 1.63 times that of the former, respectively. Regarding the failure mode, it is shown that the borehole plays a leading role in the process of fracture propagation.*

Key words: *Conventional loading, Porous coal, Deformation and failure, Influence factor*

1. INTRODUCTION

Coal exploration requires draining the gas from the coal seam. In the process of gas drainage, it is necessary to drill holes in the coal seam. However, those drill holes may collapse in the soft coal seam and this is one of the main factors affecting the gas drainage. It is caused by the local damage of the coal around the hole. This damage may be caused

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by continuous loading or creep. Zeng et al. [1] studied the mechanical properties and cracking behavior of perforated specimens under uniaxial compression. The experimental results indicated that the stress field distribution before crack initiation varies with the shape of the preexisting hole, and differences primarily exist in the configuration of the pure tension triangle and the low force region. Huang et al. [2] investigated the crack initiation, propagation and coalescence process, and acoustic emission (AE) characteristics using photographic and AE monitoring. Three failure modes were identified: splitting failure, stepped path failure, and planar failure modes. Ji et al. [3] also had a viewpoint that specimens with central holes have three different types of typical failure modes. Duan et al. [4] studied the mechanical behavior of porous brittle materials by numerical simulation. They showed that the original initiation crack is not necessarily the main crack that finally generates the failure, as heterogeneity is an important factor of local crack propagation in brittle materials.

Creep loading is quite different from conventional loading. There is an obvious yield platform and greater deformation under creep loading [5]. Under the influence of external stress, the coal around the borehole can easily become unstable, deformed and damaged, resulting in cracks and low gas drainage efficiency, which may lead to coalmine power disasters [6, 7]. Feng et al. [8] carried out a numerical simulation study on the pre-holed coal specimens and found that there were "I" type cracks in the axial direction of the prefabricated holes. According to the typical tensile failure mode of porous coal samples, the crack propagation and the failure state of porous coal samples are more complex [9, 10]. Haeri et al. [11] performed compression tests on pre-drilled Brazilian disks and rectangular specimens. The breakage load is measured for the ring type disc specimens with an axial hole with varying diameters and the distribution of the induced lateral stress is obtained. Li et al. [12] conducted uniaxial compression tests on defective coal samples with different inclination angles and found that the uniaxial compressive strength and elastic modulus increased with the increase of the inclination angle.

The original holes and fissures have a great influence on the crack propagation of coal and rock. During the loading process, tensile cracks occur in the axial direction around the borehole and at the left and right ends of the far field. Shear cracks occur in the transverse direction around the borehole, and the cracks in other parts are affected by tensile stress and shear stress [13-15]. In the case of a specimen with borehole, the area around the hole becomes a stress concentration area, which is, generally, symmetrically distributed along the hole. Complex fractures are also related to coal structure and primary fractures [16, 17]. A hole pair dominates the direction of crack propagation and has a restraining effect on the original crack, which also has a certain impact on the crack propagation around the hole [18-22]. Zheng and Wang [23] studied creep loading of porous coal under different influencing factors, and analyzed the effects of borehole diameter, borehole depth, and borehole inclination angle on creep.

Through the conventional uniaxial loading test of porous coal, this paper studies the influencing factors of deformation and failure of porous coal, mainly focusing on three aspects:

- the influence of the loading rate on deformation and failure of porous coal,
- the influence of borehole inclination on the deformation and failure of porous coal,
- the influence of borehole diameter on the deformation and failure of porous coal.

Through the above tests, the influencing factors of deformation and failure of porous coal are mastered to provide guidance for drilling construction and hole protection.

2. TEST SCHEME AND PROCESS

2.1. Test Scheme

The conventional loading test scheme of porous coal is shown in Table 1. Firstly, the conventional loading test of non-porous coal is carried out. The mechanical parameters of the coal are determined. Furthermore, basic parameters are set for subsequent tests, and samples are provided to obtain the comparative test results for porous coal. The test parameters of the non-porous coal are: loading rate of 0.5 MPa/s, drilling depth of 25 mm and drilling diameter of 5 mm. Loading tests of porous coal are carried out to investigate the following influencing factors: loading rate, borehole inclination and borehole diameter on the mechanical characteristics of porous coal. The loading rate is set to take three values: 0.1 MPa/s, 0.25 MPa/s and 0.5 MPa/s. The borehole inclination is set to be +30° and -30° compared with the horizontal borehole. The drilling diameter is set to take values: 2.5 mm, 5 mm and 10 mm. Sample shape and borehole inclination angles are depicted in Fig. 1.

Table 1 Conventional loading test scheme of borehole coal

Test name	NO.	Drilling depth [mm]	Borehole inclination [°]	Loading rate [MPa/s]	Borehole diameter [mm]
Conventional non-porous	C1	25	0	0.5	5
Loading rate	C2	25	0	0.1	5
	C3	25	0	0.25	5
	C4	25	0	0.5	5
Borehole inclination	C5	25	+30	0.25	5
	C6	25	-30	0.25	5
Borehole diameter	C7	25	0	0.25	2.5
	C8	25	0	0.25	5
	C9	25	0	0.25	10

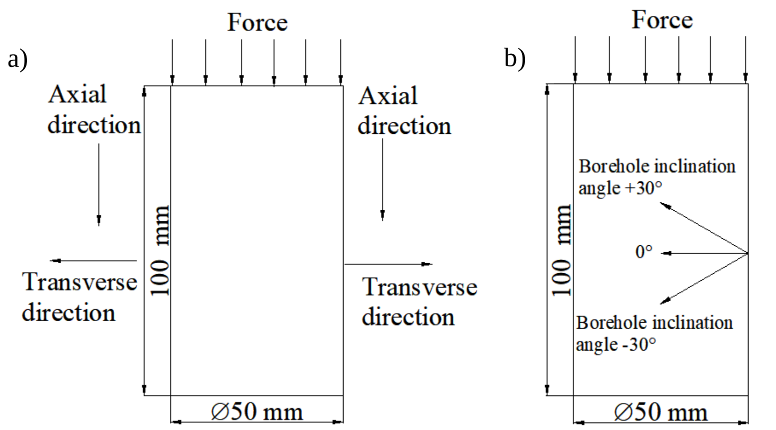

Fig. 1 Considered samples: a) Sample shape, b) Borehole inclination angles

2.2. Test Process

2.2.1 Preparatory work

Before turning on the power, the power switch on the back of the numerical control device is used to activate the preheating state. The readings of each sensor, which are displayed in the "self inspection" state, are observed via a computer to check that the system is operative. Upon confirming it, the cooling water valve is opened and the hydraulic source started. Thy system needs to run under low pressure for the first 5 minutes, after which it can operate under high pressure until the oil temperature is normal (pipeline heating), which indicates the end of the preparation stage.

2.2.2 Conducting the Experiment

Upon preparation, test pieces are installed according to different test types. The displacement sensor is adjusted to the appropriate position according to the reading value displayed in the "self-inspection" state. Depending on how the control is performed, automatic and manual control modes are distinguished. The automatic mode can be selected for normal continuous loading, while the manual mode can be selected for creep loading tests. Depending on what physical quantity is controlled, force and deformation modes are applicable. Upon selection, the available waveform will be displayed. One has to select the loading parameters and enter the test piece parameters. At the beginning of the test, the test sample needs to be preloaded so that the indenter is in full contact with the test sample, i.e. the gap is eliminated. When the preloading is completed, the software indicates that the test can be started.

2.2.3 Processing the Test Results

Rmt-301 test system provides users with conventional test result processing software. As long as the corresponding result column and the corresponding file name of the test result are entered, various test curves and data are obtained and can be printed out. Additionally, the system can also provide unprocessed test data, which can be later processed by some other data processing software to represent the results in a suitable form.

As already mentioned, the conventional loading test of non-porous coal is done first. The sample is continuously loaded at the loading rate of 0.5 MPa/s until the specimen gets damaged. Fig. 2a shows the development of the axial displacement, D_1, and the transverse displacement, D_3.

The peak axial deformation of the non-porous specimen is 0.478 mm. The resulting peak strength of uniaxial compression is 20.7 MPa. Obviously, the compressive strength of the specimen is relatively high, while the peak deformation of the specimen is small, and the specimen shows a brittle failure. In this case, the damage is mainly shear failure, with an obvious shear failure surface and single crack expansion, as can be seen in Fig. 2b.

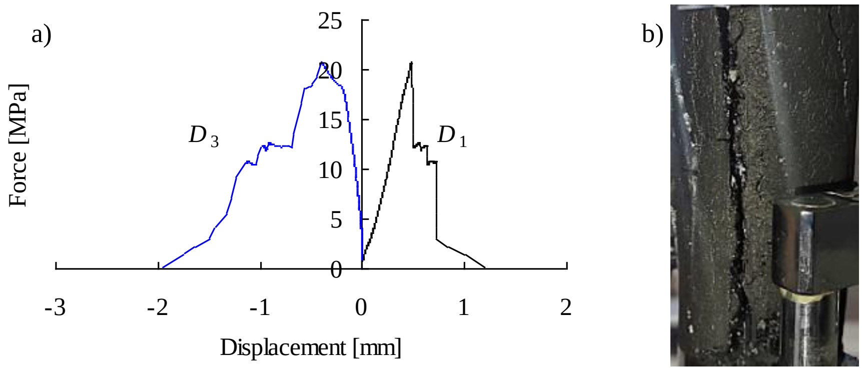

Fig. 2 Coal sample C1: a) Force-displacement curve, b) Failure mode

3. Analysis of the Test Results

3.1. Influence of Loading Rate on Deformation and Failure of Porous Coal

The deformation and failure of coal samples experienced elastic stage, plastic yield stage and failure stage. In the elastic stage, the specimen has linear compression. After plastic deformation and yield, the stress peak is reached, and the specimen is then destroyed. The stress-strain curves and failure characteristics under different loading rates are shown in Figs 3-5. When the loading rates are 0.1 MPa/s, 0.25 MPa/s and 0.5 MPa/s, the compressive strength is 14.58 MPa, 16.15 MPa and 17.54 MPa, respectively. Obviously, the higher the loading rate, the greater the compressive strength.

Regarding the damage, the fracture expansion form of porous coal is very different from that of non-porous coal. The fracture expansion of non-porous coal has an obvious shear plane, while the fracture expansion of porous coal has no obvious shear plane. The fracture expansion of porous coal is greatly affected by the borehole. Due to the formation of stress concentration areas around the borehole during the loading process, the resulting stress around the borehole is greater, so the fracture expansion is centered on the borehole. The borehole controls the main fracture expansion direction, and the fracture expansion direction and the extend of fracture are more complex.

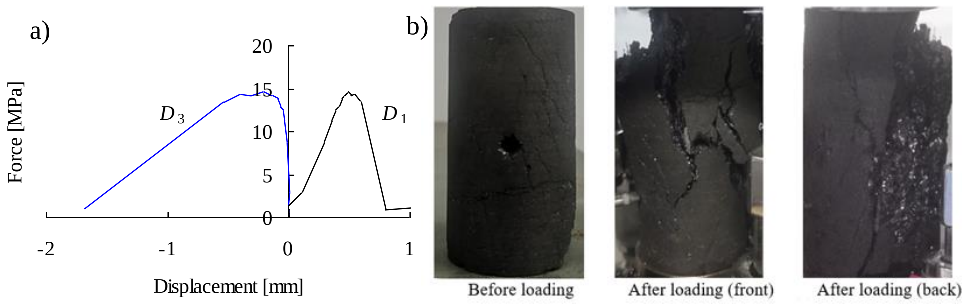

Fig. 3 Coal sample C2: a) Force-displacement curve, b) Failure mode

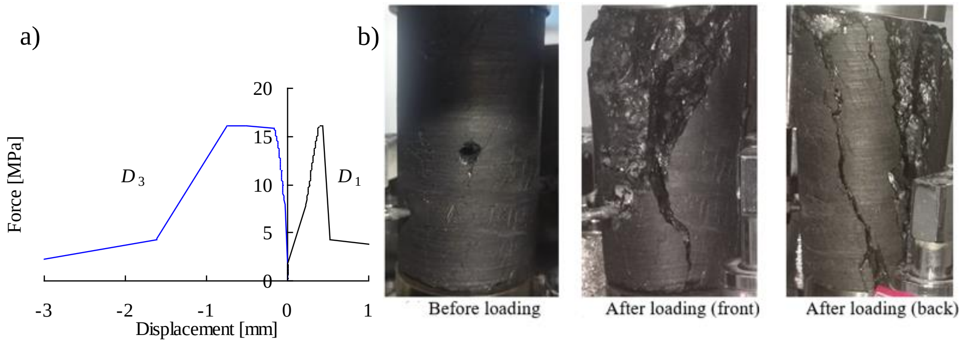

Fig. 4 Coal sample C3: a) Force-displacement curve, b) Failure mode

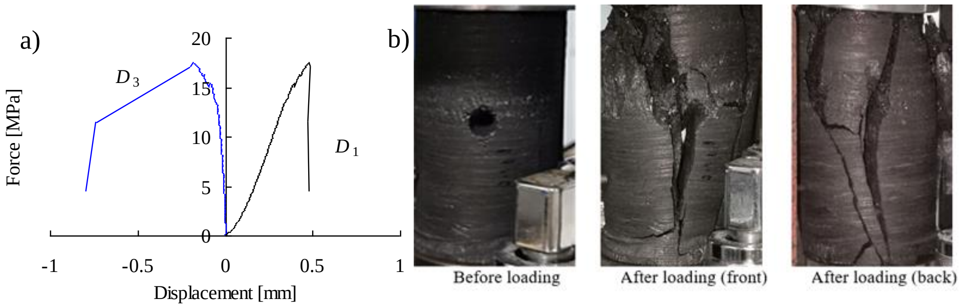

Fig. 5 Coal sample C4: a) Force-displacement curve, b) Failure mode

3.2. Influence of Borehole Inclination on Deformation and Failure of Coal with Holes

When the borehole inclination is +30°, the peak stress is 15.29 MPa and the peak deformation is 0.4744 mm. On the other hand, with the borehole inclination of -30°, the peak stress is 15.77 MPa and the peak deformation is 0.6847 mm, as shown in Figs. 6a and 7a. Compared with the horizontal boreholes, the elevation angle and depression angle of boreholes are 30°, and, in both cases, the coal strength is reduced. Compared with + 30° drilling, the deformation of -30° drilling specimen is greater when it is damaged.

From the damage state, as shown in Figs. 6b and 7b, the borehole inclination has a great impact on the damage of porous coal. When the borehole angle tilts upward by 30°, the upper part of the coal sample breaks seriously, and the fracture surface is consistent with the direction of the borehole inclination. When the drilling angle is inclined downward 30°, the lower part of the coal sample is broken more severely, and the fracture surface is consistent with the direction of the drilling inclination. It can be noticed from this failure behavior that the failure surface is consistent with the dip direction regardless of the up dip angle or down dip angle.

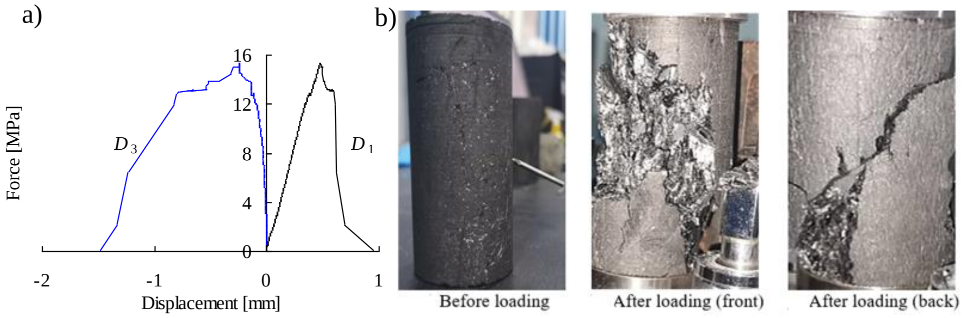

Fig. 6 Coal sample C5 (borehole, inclination angle +30°):
a) Force-displacement curve, b) Failure mode

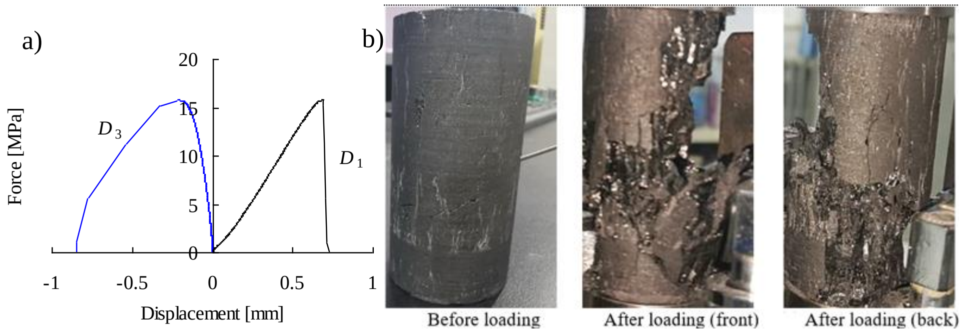

Fig. 7 Coal sample C6 (borehole, inclination angle -30°):
a) Force-displacement curve, b) Failure mode

3.3. Influence of Borehole Diameter on Deformation and Failure of Porous Coal

With an increased borehole diameter, the lateral deformation is greater and the damage is more pronounced (Figs. 8-10). Changing the borehole diameter from 2.5 mm, via 5 mm to 10 mm, the peak stress is 18.93 MPa, 17.03 MPa and 10.55 MPa, respectively. The peak deformation is 0.6188 mm, 0.43635 mm and 0.7435 mm, respectively. The transverse deformation is 0.1007 mm, 0.0797 mm and 0.1303, mm respectively. It can be seen from the above test results that, with the increasing borehole diameter, the compressive strength decreases slightly, but the deformation is influenced by some factors, such as original cracks, impurities, etc., exhibiting certain discreteness. Comparing the results for the borehole diameters of 5 mm and 10 mm, the axial deformation and transverse deformation of the latter are 1.7 times and 1.63 times that of the former, respectively.

When the borehole diameter is small, the borehole has little effect on the coal sample structure, the compressive strength is still large, and the transverse deformation has little change compared with the loading of non-porous coal sample. When the borehole diameter is large, it has a great impact on the coal sample structure, the compressive strength decreases. When the drilling diameter is 10 mm, the compressive strength is 10.55 MPa, which represents a decrease of 44.3% compared to the compressive strength (18.93 MPa) obtained in the case with the drilling diameter of 2.5 mm. From the perspective of failure characteristics, when the diameter of the borehole is small, it has the influence of the borehole and also shows certain shear characteristics. The expansion of the fracture along the vicinity of the borehole is not obvious. When the borehole diameter is large, the main fracture expands centered on the borehole.

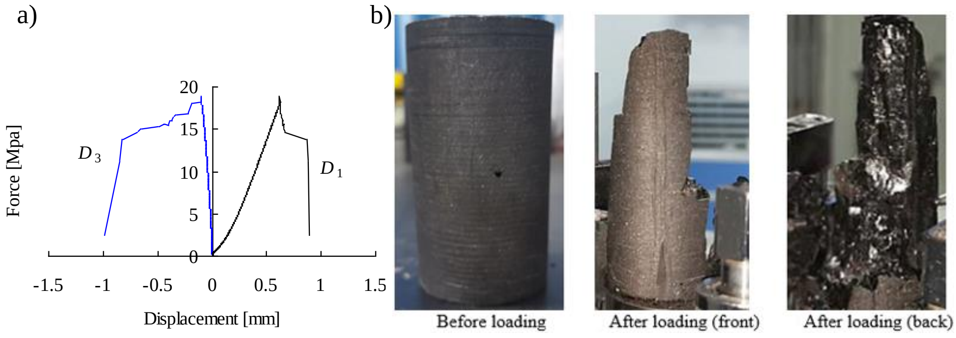

Fig. 8 Coal sample C7: a) Force-displacement curve, b) Failure mode

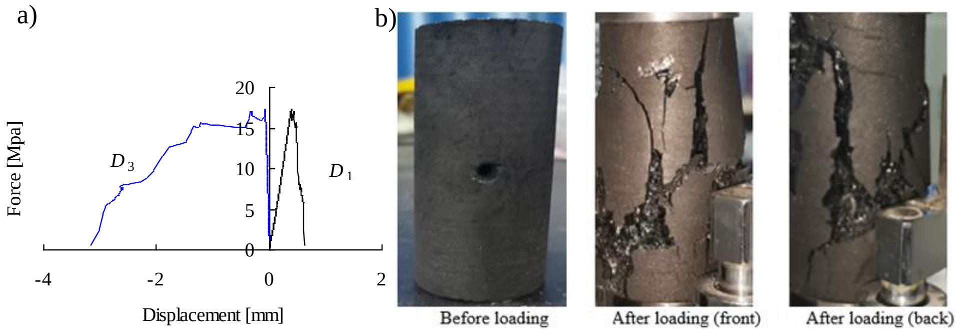

Fig. 9 Coal sample C8: a) Force-displacement curve, b) Failure mode

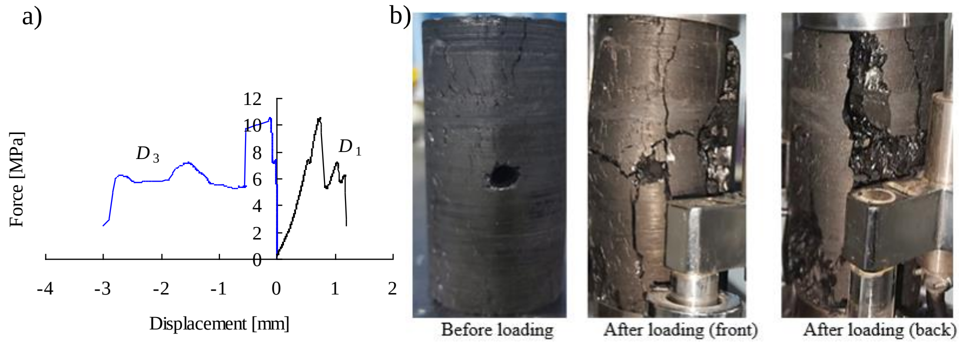

Fig. 10 Coal sample C9: a) Force-displacement curve, b) Failure mode

4. CONCLUSION

Testing coal samples with boreholes of different parameters performed to determine the resulting stress and deformation are of practical guiding significance for better understanding of the dependence between the stress and deformation states around the coal seam boreholes. Through the conventional loading test of porous coal, the effects of various influencing factors on the mechanical properties of porous coal are studied, and the following conclusions are made:

- With the loading rates of 0.1 MPa/s, 0.25 MPa/s and 0.5 MPa/s, the resulting compressive strength is 14.58 MPa, 16.15 MPa and 17.54 MPa, respectively. Hence, with the increasing loading rate, the strength of porous coal also increases, which is consistent with the effect of loading rate on non-porous coal.
- The test results of the uniaxial loading test of coal samples with drilling inclination of +30° and -30° show that the coal samples with holes at a certain inclination angle are easier to damage than the coal samples with horizontal holes. The failure surface is consistent with the inclination angle, and the specimens with the upward inclination angle are easier to damage compared to those with the downward inclination angle.
- The diameter of the drill hole has a great influence on the peak stress and peak deformation of coal. When the diameter of the drill hole is small, its influence on the structure of coal sample is small, the compressive strength is still large, and the deformation changes little compared with that of the coal sample without a hole. With higher values of the borehole diameter, a significant impact on the coal sample structure is noticed and the compressive strength decreases. Compared with the loading of the non-porous coal sample, the deformation increases significantly. Especially when the borehole diameter is 10 mm, the compressive strength decreases significantly and the axial deformation and transverse deformation increase.
- According to the crack propagation state of coal sample in the loading process, the failure state of non-drilled coal sample has an obvious shear plane and a simple failure form, while the failure state of a drilled coal sample in the crack propagation process is complex.

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