Crack Propagation Mechanism of Hydraulic Fracturing in Thick-Bedded Sandstone Coal Mine Roof

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Abstract: The thick-bedded sandstone roof of the Bayangaole coal mine is at risk of rock burst accidents. Hydraulic fracturing technology has been used to prevent these accidents by controlling coal seam roof collapse. To research the crack propagation mechanism of hydraulic fracturing in thick-bedded sandstone roof, hydraulic fracturing experiments are conducted on thick roof sandstone with a hole drilled in the center, and RFPA2D-Flow software is adopted to conduct numerical simulations of the formation mechanism and spatial distribution of hydraulic fracture cracks in bedded sandstone. The physical experiments reveal that cracks are generated from the weak parts and stress-concentration area of the hole wall due to hydraulic pressure; main cracks either form along the bedding or spread toward the bedding. Numerical simulations show that the crack propagation mechanism for specimens without preset slotting is consistent with the experimental results. For the preset-slot specimens, micro-cracks generate in the region where tensile stress is applied, which gradually increase and penetrate the preset slotting tip; the specimen continues to crack until failure occurs. When the main crack encounters the bedding, it turns and propagates along the bedding when the bedding angle is small, which results in tensile failure. However, when the angle is large, the crack passes directly through the bedding, forms a new hydraulic crack, and continues to propagate forward, which results in the tensile failure of the cutting bedding.

1. Introduction
In the process of coal mining, hard roofs such as thick sandstone, conglomerate, or limestone are often encountered, which have high strength, large thickness, good integrity, and strong self-bearing capacity. If the hard roofs cannot be effectively controlled, large-scale roof collapse may occur as well as rock burst, coal and gas outburst, and other coal-rock dynamic disasters. These are the main limitations of efficient and safe mine production [1,2]. After a long development period [3], hydraulic fracturing technology is now widely applied to control coal seam dynamic disasters [4, 5, 6, 7]. In particular, directional hydraulic fracturing technology can regulate the hydraulic crack direction by preserving the cutting joint around the borehole. This method has achieved good field application results [8, 9, 10]. The directional hydraulic fracturing technique, developed in Poland to control the rigid and difficult...
of fracture initiation and propagation. Many scholars have conducted extensive research on the mechanism and application of directional hydraulic fracturing in coal mines. Researchers have demonstrated the effectiveness of directional fracturing through field tests. Huang et al. [11] conducted a field test of directional hydraulic fracturing in the Dashan Tashan coal mine and found that pre-cutting plays a directional role in the initiation process of rock hydraulic fracturing, and the propagation of cracks is affected by in-situ stress. Feng et al. conducted underground tests of directional hydraulic fracturing [12] and found that a preset notch could effectively reduce the required pressure of crack initiation. Kayupov et al. [13] carried out hydraulic fracturing tests and numerical simulations on granite specimens and found that failure was due to the propagation of primary micro-cracks around the hole walls. Cheng et al. [14] revealed that the initiation pressure increases due to an increase in both the horizontal-stress difference coefficient and the slotting deviation. He et al. [15] conducted microscopic numerical simulations and found that the heterogeneity of rock mass influences the trajectory of hydraulic fracture cracks. Despite the increasing sophistication of hydraulic fracturing in mining applications [16], research is lacking with respect to the sedimentary diagenesis of obvious heterogeneity: the roof rocks of coal seam are mostly sedimentary rock, forming a discontinuous weak surface (such as joints and bedding) with a certain inclination and thickness. Studies show that bedding has a significant impact on the mechanical properties of rock mass [17,18], e.g., the motion law of the roof, breaking mode, and energy transfer. Therefore, it is vital to study the crack propagation mechanism of hydraulic fracturing in rock with bedding. In addition, studies on the failure mechanism of bedded rocks [19,20,21] indicate that the bedding plane plays a controlling role in rock failure. Niapdou et al. [22] studied the mechanical anisotropy and failure characteristics of bedded shale by triaxial compression tests and found that the failure modes of bedded shale are mainly shear failure and tension failure. The failure modes are dependent on the confining pressure and direction of external loading. Some scholars have studied the damage evolution mechanism of bedded rock. For example, Zhao et al. [23] studied the variation of mechanical parameters, deformation, and failure characteristics of marble under the influence of different external loads and bedding angles. Dai et al. [24] conducted three-point bending experiments and found that the fracture and sliding of the rock-interface layer have a crack-stopping effect on crack propagation; moreover, the crack tip migrates along the interface layer.

Previous research has provided a theoretical foundation for the initiation and application of hydraulic fracturing for bedded rocks; however, research is lacking with respect to the meso-damage mechanism of hydraulic fracturing cracks in bedded rocks. The Bayangaole coal mine in Inner Mongolia has a typical hard roof made of thick sandstone with a relatively developed bedding. Here directional hydraulic fracturing technology has been utilized to control the thick hard-rock sandstone roof. In this paper, sandstone rock samples are obtained from the Bayangaole coal mine. Hydraulic fracturing tests are conducted to study the cracking failure behavior of bedded sandstone in the mining area under hydraulic action. At the same time, RFPA2D-Flow software is adopted to conduct numerical simulations and study the evolution and mesoscopic expansion mechanism of cracks under hydraulic fracturing.

2. Research Background and Sandstone Sample Pretreatment
The Bayangaole coal mine is located in Wushen Banner, Ordos City, Inner Mongolia Autonomous Region, with the geographic coordinates of 109°19′00″ to 109°26′22″E and 38°42′45″ to 38°46′58″N. The range of the mine is delineated by six inflection points, the plane shape is a regular polygon, the length from east to west is 10.64 km, the width from south to north is 7.79 km, and the area is 65.2734 km², as shown in Fig. 1. There are multiple thick hard roofs within 0.55–32.08 m above No. 3-1 coal seam in the mining area among the Nos. 3-1, 4-1, 4-2, and 5-1 coal seams. The roof lithology is mainly sandy mudstone. The impact propensity appraisal of the No. 3-1 coal seam and roof is high, which suggests a strong impact risk. At present, the 311103 working face of the No. 3-1 coal seam is in the process of mining. The sandstone layer on the roof above the auxiliary withdrawal channel of
the working face is thick and hard and affected by the stress distribution of the No. 3-1 coal roadway-protection pillar by the hanging roof in the goaf of the 11-panel area. Therefore, it is the key work to reduce the risk of rock burst and ensure production safety.

A large number of theoretical studies and field practices show that directional hydraulic fracturing technology can weaken roof strength [4-6]. Therefore, directional hydraulic fracturing technology can be applied to treat the hard and thick sandstone layer over the mined-out area at the 311103 working face. In the early stage of hydraulic fracturing, under the action of high-pressure water, the roof preferentially cracks along initial prefabricated slots and expands outwards. With an increase in fracturing time and water pressure in the hole, the crack trend is affected by the original stress state, mining stress, and heterogeneity of the rock mass.

To study the hydraulic fracturing effect of roof sandstone, samples were obtained from the roof of the 311103 coal seam at a depth of 600 m and processed into 50 × 100-mm cylinders with an 8-mm borehole drilled into center at depths of 60, 70, 80, and 90 mm, which is shown in Fig. 2. The rock belongs to coarse sandstone with bedding, and its main components are quartz, feldspar, and lithic debris. The natural compaction degree of the rock is weak; the grains have a weak degree contact with pore cementation. Fig. 2 shows that there are obvious layers on the outer surface of each specimen group of specimens.
3. Experimental Study of Hydraulic Fracturing in Bedded Sandstone

3.1. Experimental process
A triaxial compression system was used to conduct the hydraulic fracturing test, which is shown in Fig. 3. This system simulated ground pressure by controlling the axial and confining pressure. Fracturing fluid was injected into the reserved hole in the rock to observe the law of hydraulic crack initiation and propagation.

Before performing the fracturing experiment, two gaskets were fixed in the hole with glue, and the oil intake pipe was reserved. High strength resin glue was added to the hole to seal it. A heat shrinkage pipe was wrapped around the rock, and the ends were sealed with pipe hoops. The ratio of guar-gum quality to water quality was set as 1:50 to configure the fracturing fluid. A red tracer was added to observe the surface hydraulic cracks and the internal hydraulic conveying channel.

Fracturing fluid was injected into rock by a supercharger. Pressure was applied to the round hole at a rate of 0.01 mL/s by flow control until the sample was destroyed, and the resultant force–time curve was recorded. After the experiment was completed, a camera was used to record the shape of hydraulic cracks inside the rock.

3.2. Experimental results
Fig. 4 shows the pressure variation curve for the samples, from which it is evident that the failure pressure is 29.09, 31.33, 32.02, and 29.59 MPa for a hole depth of 60, 70, 80, and 90 mm, respectively. When calculating the crack initiation pressure during hydraulic fracturing, the confining pressure should be subtracted. The average crack initiation pressure is about 24 MPa. In addition, the pressure-rise slope of each specimen is around 0.071. The failure pressure and pressure-rise slope both indicate that the influence of hole depth on crack initiation pressure is small and can thus be ignored.
Fig. 4. Pressure–time curve, where \( k \) denotes hole depth.

Fig. 5 shows the failure modes, from which it is evident that, when the hole depth is 60 mm, the cracking point is 51.07 mm away from the specimen top, and the resulting main crack is inclined at an angle of 65° with the horizontal plane. The crack angle is similar to the bedding angle, indicating that the specimen is destroyed along the bedding plane. When the hole depth is 70 mm, the cracking point is 69.89 mm away from the specimen top, and the resulting main crack is inclined at an angle of 40° with the horizontal plane, which is almost the same as the bedding angle, i.e., the specimen is broken along the bedding plane. When the hole depth is 80 mm, the cracking point is 73.89 mm away from the specimen top, and the resulting main crack is inclined at an angle of 30°. For this depth, the rock does not crack along the bedding plane but at an angle perpendicular to the bedding plane. When the hole depth is 90 mm, the cracking point is 85.2 mm away from the specimen top, and the resulting main crack is inclined at an angle of 45°, which is close to the bedding angle, and, as such, the specimen is destroyed along the bedding plane. The above analysis shows that three of the specimens cracked along the bedding direction and only one through the bedding, which suggests that cracking is related to bedding angle.

Fig. 5. Specimen failure modes.
Fig. 6 shows the internal and surface specimen damage. Indeed, the internal cracking point for all specimens is in the stress-concentration area at the hole bottom, indicating that cracking is caused by stress-concentration. Comparing Fig. 6 with Fig. 5, it is evident that rock fracture is mainly caused by the expansion of the defective position in the bedding area due to stress-concentration at the bottom of the hole. The rock particles in the weak area are cemented by clay minerals and are likely to swell or soften. Under the action of water, the bedding surrounding the stress-concentration softens, which results in the preferential initiation of defects within the bedding, then forming the initial main crack required for propagation. When the hole depth is 90 mm, the main fracture plane is not along the bedding plane at the beginning of crack propagation, but eventually has a failure trend toward bedding. As such, it can be concluded that the bedding has a large impact on the specific mode of hydraulic crack propagation.

\[ \text{(a) } k = 60 \text{ mm (b) } k = 70 \text{ mm (c) } k = 80 \text{ mm (d) } k = 90 \text{ mm} \]

**Fig. 6.** Specimen interior damage.

### 4. Mechanism of Hydraulic Crack Propagation

To further study the failure mechanism of hydraulic fracturing, RFPA2D-Flow software was adopted to conduct numerical simulations. RFPA2D-Flow can simulate the basic seepage characteristics of rock mass and analyze the rock-layer fluid–solid coupling problem. The fluid in the simulated material medium should follow Biot's seepage theory \[25\]. Considering the change of material permeability caused by stress, the basic equations of seepage stress coupling can be expressed as

1. **Equilibrium equation**
   \[ \sigma_{ij,j} + \rho X_{ij} = 0 \quad (i, j=1,2,3) \]  
   \[ (1) \]

2. **Geometric equation**
   \[ \varepsilon_y = \frac{1}{2} (u_{ij,j} + u_{ji,j}) \quad \varepsilon_v = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33} \]
   \[ (2) \]

3. **Constitutive equation**
   \[ \sigma_y' = \sigma_y - ap \delta_y = \lambda \delta_v \varepsilon_v + 2G \varepsilon_y \]
   \[ (3) \]

4. **Seepage equation**
   \[ K \nabla^2 p = \frac{1}{Q} \frac{\partial p}{\partial t} - a \frac{\partial \varepsilon_v}{\partial t} \]
   \[ (4) \]

5. **Coupling equation**
   \[ K(\sigma, p) = \xi K_0 e^{-\beta(\sigma_1^3 - ap)} \]
   \[ (5) \]

where \( \rho \) is the physical density, \( \sigma_{ij} \) and \( \sigma_{ij}' \) denote the total stress and effective stress, respectively, \( \varepsilon_v \) and \( \varepsilon_{ij} \) denote the volume strain and positive strain, respectively, \( \delta \) is the Kronecker constant, \( G \) and \( \lambda \) denote the shear modulus and lame coefficient, respectively, \( Q \) is the Biot constant, \( K \) and \( K_0 \) are the initial value and permeability coefficient, respectively, \( p \) is the pore-pressure, \( \beta \) is the coupling coefficient, \( \xi \) is the jump coefficient of the permeability coefficient, and \( a \) is the pore-pressure coefficient. A large number of tests show that the rock permeability is significantly related to stress-damage evolution.

#### 4.1. Simulation research

According to the specimen parameters in the experiment, a two-dimensional plane-strain numerical model without a preset notch was established to model the cross section of a cylinder with an outer diameter (D) of 50 mm and an inner diameter (d) of 8 mm, as shown in Fig. 7. Directional hydraulic fracturing is often used to control the coal roof in the Bayangao coal mine. Therefore, to compare the law of hydraulic crack propagation for specimens with/without preset notching, an additional model was established with preset notching; two grooves with a length of \( a = d/4 \) were set at both ends of the
circular hole of the model.

![Model without preset notching](image1)

(a) Model without preset notching (b) Model with preset notching

**Fig. 7.** Hydraulic fracturing analysis model.

The two models were divided into 170 × 170 meso-units. As shown in Table 1, the mechanical parameters of rock were obtained by a uniaxial compression test and Brazilian disk test. The parameter that reflects the uniformity of mechanical properties of materials is 3 [26] (The homogeneity of rock material is generally between 2 ~ 5), and the increment of the pore-pressure coefficient was calculated to be 0.6, which is equal to the increase of water pressure in the pore at 0.1 MPa per step until crack propagation results in specimen failure.

**Table 1.** Model mechanical parameters.

| Parameter                  | Value |
|----------------------------|-------|
| Compressive strength /MPa  | 43.1  |
| Elastic modulus /GPa       | 12.24 |
| Poisson's ratio            | 0.17  |
| Homogenization             | 3     |
| Friction angle /°          | 30    |
| Permeability coefficient   | 0.1   |
| Coupling coefficient       | 0.1   |
| Pore-pressure coefficient  | 0.6   |

4.2. Simulation results and analysis

The simulation and experiment results are basically consistent. The simulation results show that the cracking pressure of specimens without a preset notch is about 23 MPa, and that of specimens with a preset notch is smaller at 17 MPa, which is accurate with respect to actual situations.

Fig. 8 shows the maximum principal-stress diagram during failure. The failure process of the two models can be divided into three stages: stress accumulation, stable crack growth, and specimen failure. First, in the stress accumulation stage, a ring stress-concentration zone forms around the circular hole in the specimen without a preset notch, and the maximum stress is distributed radially. The stress-concentration on both sides of the grooves of preset notch specimens is obvious, which makes the tip area of the preset notch bear sector-like distributions of tension stress. In this stage, the elements of both models will not be destroyed, which corresponds to the first stage of acoustic emission (AE) characteristics in Fig. 9, where the AE phenomenon does not occur.

With an increase in water pressure, the model enters the stage of stable crack growth. For the specimen without a preset notch, randomly distributed micro-cracks (step 39) appear in the weak parts within the ring stress-concentration zone. With a further increase in water pressure, the micro-cracks penetrate each other to form macro-cracks, which gradually expand. With a further increase in water pressure, the symmetrical direction of the main crack produces a strong tensile stress and another main crack, which leads to the formation of symmetrical crack propagation (step 68-5). For the specimen with a preset notch, scattered micro-cracks (step 30) are first generated in the tension zone at the tip of preset notch. With a further increase in water pressure, the micro-cracks begin to connect with each other and penetrate the tip of the pre-slit. The specimen cracks almost simultaneously from the preset notch at
both ends. However, the cracks at both ends are not symmetrical due to the non-uniformity of the material but, rather, propagate along the horizontal direction (step 40-5). In this stage, both models begin to demonstrate AE phenomena, the intensity of which increases gradually and corresponds to the second stage of AE characteristics in Fig. 9.

When the water pressure is increased to a critical degree (23 MPa for specimen without a preset notch and 17 MPa for preset notch specimen), the crack tip of both models demonstrates bifurcation. Several irregular cracks sprout at the tip of main crack, indicating that the crack will enter the stage of instability and expansion, and the specimen begins to lose stability gradually (step 68-13 for the specimen without a preset notch and step 40-16 for the preset notch specimen). At this time, with a constant pressure, the crack continues to undergo progressive expansion, and the AE have a large kick in this period, corresponding to the third stage of AE characteristics in Fig. 9.

![Fig. 8. Maximum principal-stress diagram during failure.](image)

![Fig. 9. AE characteristic curve.](image)

Fig. 10 shows the distribution of pore water pressure during the failure phase of the two models, from which it is evident that the maximum water pressure appears around the circular hole before the specimen starts to crack. When the water pressure is increased further, the specimens begin to crack. Water in the cavity converges to the main crack tip due to the continuous driving of water pressure. Although water flow transfers along the crack, the maximum water pressure appears on the crack surface, which forces the crack to propagate toward both sides. When the critical failure point is
reached, the maximum water pressure of the two models has an approximate elliptical distribution.

(a) Specimen without a preset notch
(b) Specimen with a preset notch

Fig. 10. Distribution of pore water pressure.

5. Expansion Mechanism of Hydraulic Cracks in Preset Notch Specimens with Bedding

5.1. Simulation research
The experimental results show that the failure modes of specimens are different due to bedding. Therefore, the model shown in Fig. 11 was established to study the influence of bedding on the propagation of hydraulic cracks, in which two layers (with a length of \( l = 12 \text{ mm} \)) were added at both ends of the preset notch, and the bedding angle was given values of 0°, 45°, and 90°. The mechanical parameters and loading conditions are the same as those of without/with preset notch models.

Fig. 11. Hydraulic fracturing model with bedding cracks.

5.2. Simulation results and analysis
Fig. 12 shows the failure process when the bedding angle is 0°. The cracks propagate from both ends of the preset notch at almost the same time. According to the principle of minimum energy dissipation, the main crack propagates directly along the bedding and makes contact with it. In the stage of crack growth, the main crack on the right side propagates faster than that on the left. When the main crack on the right side propagates along the bedding to the outer surface of the specimen, the main crack on the left side also starts to propagate rapidly due to tension, and the specimen is unstable and fails. The hydraulic crack is influenced by material inhomogeneity, and, in the early stage, it is not straight but slightly tortuous.
Fig. 12. Maximum principal-stress diagram of specimens with a bedding angle of 0°.
Fig. 13 shows the failure process with a bedding angle of 45°. Hydraulic cracks originate from both ends of the preset notch simultaneously. At the initial stage, the hydraulic cracks generally maintain a horizontal direction, after which they gradually extend to the middle and lower parts of the bedding. After contacting the bedding, following the principle of minimum energy consumption, hydraulic cracks begin to deviate from the original direction of propagation and continue to develop obliquely along the bedding. Due to the effect of water pressure, "the cracks at the bottom bedding are a closed phenomenon. In the later stage, the cracks at the end of the bedding are not straight, but take the main crack as the backbone and spread outward in a dendritic manner.

Fig. 13. Maximum principal-stress diagram of specimens with a bedding angle of 45°.
Fig. 14 shows the failure process with a bedding angle of 90°. Again, hydraulic cracking starts from both ends of the preset notch and propagates forward. When the crack extends to a certain length, it intersects with the bedding near the middle. However, the crack penetrates through the weak bedding surface rather than along the bedding. Then, a new hydraulic crack is formed behind the bedding and propagates forward. Influenced by material inhomogeneity, hydraulic cracks are not straight but zigzag, and many branching cracks appear before the specimen is destroyed.

Fig. 14. Maximum principal-stress diagram of specimens with a bedding angle of 90°.

6. Discussion
The simulation results show that the specimen without a preset notch forms a radial stress-concentration zone around the borehole with random micro-cracks generated in the weak parts. The micro-cracks penetrate each other to form a main macro-crack, which results in specimen failure. This is consistent with the experimental results, which suggest that failure for the specimens without a
preset notch is random. In the model, the hydraulic cracks propagate symmetrically along the radial direction in general. The roughness and irregularity of the fracture surface vary greatly with mechanical properties. The bifurcation behavior of the cracks inevitably obstructs the water flow and consumption of partial energy, which also partly explains the phenomenon that the experimental value of hydraulic fracturing is higher than the theoretical value.

In the model of the preset notch specimen, stress-concentration occurs on both sides of the grooves, which means the crack tip is subjected to tension stress. Then, micro-cracks occur and gradually penetrate the notch tip. The micro-cracks start from the tip of the notch and propagate continuously until specimen failure occurs. The results show that the initiation pressure of the preset notch specimens is lower than that of the specimens without a preset notch, and stratification has a controlling effect on the propagation of hydraulic cracks. If the hydraulic main crack encounters the bedding, when the bedding angle is between 0° and 45°, the crack will gradually turn and propagate along the bedding, and the bedding will fail due to tensile stress; when the bedding angle is greater than 45°, the crack passes through the bedding directly, forms a new hydraulic crack behind the bedding, and continues to develop in the original direction, resulting in tensile failure within the cutting bedding. Therefore, the bedding of thick sandstone should be considered in the design of hydraulic fracturing parameters in the Bayangaole coal mine.

7. Conclusion

In this paper, laboratory hydraulic fracturing experiments were conducted with samples of hard roof sandstone taken from the Bayangaole coal mine, and numerical simulations were performed by RFPA2D-Flow software. The failure law of hydraulic fracturing was studied, and the conclusions outlined below were drawn.

(1) According to the experimental results, specimen failure was caused by the propagation of micro-cracks in the stress-concentration zone. The injected water softened the bedding in the stress-concentration zone and resulted in the formation of micro-crack defects that combined and formed a main crack, which propagated throughout the specimen. The main crack underwent directional bedding propagation, but the specific mode of propagation varied greatly when the angle between the initial main crack and bedding was changed.

(2) According to the simulation results, the specimens without a preset notch generated micro-cracks in the weak parts of the stress-concentration area, which increased in size and penetrated each other to form a main macro-crack that ultimately resulted in specimen failure. The failure of the preset notch specimen generated micro-cracks in the tension zone that penetrated through the crack tip. The initiation pressure was significantly lower compared with the specimens without a preset notch.

(3) Heterogeneity should be considered in the engineering design of hydraulic fracturing. Stratification has a controlling effect on hydraulic fracturing crack propagation. When the main crack encounters the bedding in the process of propagation, the tensile failure along or cutting through the bedding is dependent on the angle between the main crack and bedding.

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