Detailed Response to Reviewers

Dear Editors and Reviewers,

Thank you very much for your useful comments and suggestions on our manuscript. We have modified the manuscript accordingly, and detailed responses are listed below point by point.

Comments of Editors

Please ensure that your manuscript is cut down to the prescribed word limits. Authors maybe charged extra for exceeding word limits and the publication maybe delayed.

□ We have shorten the manuscript within 4000 words to meet the requirement of your journal.

Please ensure that you have followed the Current Science style for quoting references. If you have not followed the Current Science style, the paper maybe returned to you and publication maybe delayed.

□ We exactly follow the Current Science style for quoting references.

Comments of Reviewers

Jiang et al. presented a very interesting study on the effects of the bedding on the fracture toughness of coal, and hydraulic fracture initiation and propagation in coalbed methane reservoirs. As we know, the hydraulic fracturing in CBM reservoirs is much more difficult than that in the shale gas reservoirs. It is mainly because the poor property of CBM reservoir, such as low strength, strong anisotropy, and small thickness. The bedding serviced as the main characteristic of coal, which has a low strength and has notable effects on the fracture toughness. However, it is studied rarely. In the paper, the authors studied the fracture toughness of a coal systematically, and numerically investigated the effects of the bedding on the hydraulic fracturing in CBM reservoirs. It is a contribution to understand the effects of the bedding on the coal property and on the hydraulic cracking in CBM reservoir. This paper is well prepared and written, and the experimental and numerical simulation results are reliable. I am inclined to accept it for the publication after a minor revision. Some suggestions are proposed:

□ Thank you for the positive comments.

1) Hydraulic fracturing is suggested as the key words.

□ We have added “Hydraulic fracturing” as a key word in the revised manuscript.

2) The subscripts of the parameters used in the equations should be italic.

□ We have revised.

3) Please delete "We do not take type II cracks into consideration." It gives no useful information.

□ We have deleted it.

4) A reference is suggested for "Its depth and width are 20 mm and 1.5 mm, respectively."

□ We have added a reference.

5) A careful proof-reading is suggested to make the paper more fluent.

□ A careful proof-reading has been made by a professor with native language of English.

We express our sincere thanks and respects again to the editors and reviewers for your hard work on our manuscript. We hope our explanations and responses allow reviewers to easily understand the main ideas in our manuscript. If there is still some confusion or mistakes remain, please tell us. We will try our best to explain and revise. We look forward to your positive response.

Sincerely,

Tingting Jiang, Jianhua Zhang, Gang Huang, Hao Wu

Effects of bedding on hydraulic fracturing in coalbed methane reservoirs

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Bedding is a special structure of coal, which has notable effects on the mechanical parameters of the coal and also on the hydraulic facture propagating in coalbed methane reservoirs. To investigate the effects of the bedding on the anisotropic characteristics of the coal fracture toughness, three point bending tests have been carried out on raw coal specimens. The results indicate that the fracture toughness and failure modes of the specimens both have strong anisotropy due to the bedding. A geological geomechanical model of a coalbed methane (CBM) reservoir is built taking into account the effect of bedding to study the hydraulic fracture propagation and the influence of bedding on the fracture network. The hydraulic fracture initiates at the end of the perforation and tends to bifurcate and swerve at the bedding to produce induced fractures. Ultimately, these fractures form a complicated fracture network. The fracture toughness of bedding has great influence on hydraulic fracture geometry. The fracture is likely to bifurcate and swerve at the bedding to form multiple secondary fractures with larger bedding fracture toughness.

Keywords: Coalbed methane, coal seam, fracture toughness, three point bending test, numerical simulation, hydraulic fracturing

IN coalbed methane (CBM) reservoirs the bedding always fractures before the matrix for its weak cementation[1,2]. This has a significant impact on the reservoir exploitation, mechanical properties, stress distribution of borehole surrounding rock and crack initiation[3,4]. Complex fracture geometry can be formed at the bedding during hydraulic fracture propagation[5,6]. Therefore, it is of great significance to study the effects of bedding on hydraulic fracture propagation in CBM reservoirs. Several studies have been carried out in related fields.

Jeffrey *et al.*[7]studied the influence of bedding, face cleats and joints on the fracture geometry. Gu *et al.*[8] proposed an interfacial slip model based on the displacement discontinuity method. Cho *et al.*[9] researched the influence of the transverse isotropic plane on deformation and strength anisotropy of Boryeong shale. Liu *et al.*[10] comprehensively studied the influence of horizontal bedding on tensile and compressive mechanical properties in a coal seam. Guo *et al.*[11] confirmed that a fracture network can be easily formed in shale when the hydraulic fracture does not extend along the natural bedding plane. Heng *et al.*[12] studied the effect of bedding plane orientations on shear strength of shale. Jiang *et al.*[13] simulated the hydraulic fracturing by carrying out true triaxial tests on cubic raw coal specimens. Ma *et al.*[14] studied the effect of bedding on the anisotropic permeability of shale. Zou *et al.*[15] concluded the bedding had notable effects on the injection pressure and hydraulic fracture height during the hydraulic fracturing in shale formation. However, the effects of bedding on hydraulic fracturing in CBM reservoirs are relatively. This leads to the effects of the bedding on the fracturing in CBM reservoirs not being well understood.

On account of the complex structural characteristics of bedding in CBM reservoirs, the anisotropy of Mode I fracture toughness is analyzed based on the stress field distribution characteristics of a crack tip in an anisotropic material. Three point bending tests have been carried out on samples cored from Jiaozuo coal mine. The mechanical properties are obtained and the effects of bedding on the anisotropic characteristics of the coal seam are investigated. To study the effects of bedding on the hydraulic fracturing, a geological geomechanical model based on the target reservoir geological characteristics is developed using RFPA (Realistic Failure Process Analysis) software[16]. The propagation rules of the cracks and the influence of bedding on the fracture network in a CBM reservoir are analyzed. Research results can provide a reference to understand the important role of bedding in forming the network cracks in CBM reservoirs during hydraulic fracturing.

Crack-tip stress field in an anisotropic material

A CBM reservoir has the characteristics of strong brittleness and very poor plasticity, so we can analyze the instability extension of a hydraulic fracture based on linear elastic fracture mechanics (LEFM)[17]. Stress intensity factor is not only an important parameter to express the crack-tip stress, but also an important index to judge the crack instability state in LEFM[18]. Therefore, it is of great significance to analyze the distribution characteristics of the crack-tip stress field in an anisotropic material, understand the anisotropy of coal rock fracture toughness, and further study the complex extension rule of a hydraulic fracture. Figure 1 shows the local coordinate diagram of the crack tip in an anisotropic material. The length of the fracture is $2a$.

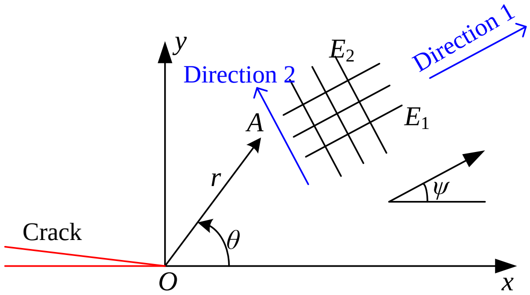


Figure 1. Crack tip diagram in an anisotropic material (the coordinates of point A are (r, θ)).

The basic differential equation of the generalized plane stress problem is[19]

$$a_{11}\frac{\partial^4 F}{\partial y^4}+a_{22}\frac{\partial^4 F}{\partial x^4}-2a_{26}\frac{\partial^4 F}{\partial x^3\partial y} -2a_{16}\frac{\partial^4 F}{\partial x\partial y^3}+(2a_{12}+a_{66})\frac{\partial^4 F}{\partial x^2\partial y^2}=0, \quad (1)$$

where a_{ij} is flexibility coefficient; F is stress function of anisotropic material plane problems.

The basic differential equation of the generalized plane strain problem is obtained by replacing a_{ij} with β_{ij}. The relationship between β_{ij} and a_{ij} is

$$\beta_{ij}=a_{ij}-\frac{a_{i3}a_{j3}}{a_{33}} \quad (2)$$

where β_{ij} is the reduction flexibility coefficient.

For orthotropic material, eq. (1) can be simplified as

$$\frac{1}{E_1}\frac{\partial^4 F}{\partial y^4}+\frac{1}{E_2}\frac{\partial^4 F}{\partial x^4}+(\frac{1}{G_{12}}-\frac{2v_2}{E_2})\frac{\partial^4 F}{\partial x^2 y^2}=0 \quad (3)$$

where E_1 is the elasticity modulus in transverse isotropic plane, Pa; E_2 stands for the elasticity modulus perpendicular to the transverse isotropic plane, Pa; G_{12} is the shear modulus perpendicular to the transverse isotropic plane, Pa; v_2 is the Poisson's ratio perpendicular to the transverse isotropic plane.

The asymptotic solutions of the crack tip stress field are[20]

$$\begin{cases} \sigma_x = \dfrac{K_I}{\sqrt{2\pi r}} \mathrm{Re}\left[\dfrac{\Sigma_1\Sigma_2}{\Sigma_1-\Sigma_2}\left(\dfrac{\Sigma_2}{\eta_2} - \dfrac{\Sigma_1}{\eta_1} \right) \right] \\ \qquad + \dfrac{K_{II}}{\sqrt{2\pi r}} \mathrm{Re}\left[\dfrac{1}{\Sigma_1-\Sigma_2}\left(\dfrac{\Sigma_2^2}{\eta_2} - \dfrac{\Sigma_1^2}{\eta_1} \right) \right] \\ \sigma_y = \dfrac{K_I}{\sqrt{2\pi r}} \mathrm{Re}\left[\dfrac{1}{\Sigma_1-\Sigma_2}\left(\dfrac{\Sigma_2}{\eta_2} - \dfrac{\Sigma_1}{\eta_1} \right) \right] \\ \qquad + \dfrac{K_{II}}{\sqrt{2\pi r}} \mathrm{Re}\left[\dfrac{1}{\Sigma_1-\Sigma_2}\left(\dfrac{1}{\eta_2} - \dfrac{1}{\eta_1} \right) \right] \\ \tau_{xy} = \dfrac{K_I}{\sqrt{2\pi r}} \mathrm{Re}\left[\dfrac{\Sigma_1\Sigma_2}{\Sigma_1-\Sigma_2}\left(\dfrac{1}{\eta_1} - \dfrac{1}{\eta_2} \right) \right] \\ \qquad + \dfrac{K_{II}}{\sqrt{2\pi r}} \mathrm{Re}\left[\dfrac{1}{\Sigma_1-\Sigma_2}\left(\dfrac{\Sigma_1}{\eta_1} - \dfrac{\Sigma_2}{\eta_2} \right) \right] \end{cases} \quad (4)$$

The asymptotic solutions of the crack tip displacement field are

$$\begin{cases} u = K_I\sqrt{\dfrac{2r}{\pi}} \mathrm{Re}\left[\dfrac{1}{\Sigma_1-\Sigma_2}\left(\Sigma_1 p_2\eta_2 - \Sigma_2 p_1\eta_1 \right) \right] \\ \qquad + K_{II}\sqrt{\dfrac{2r}{\pi}} \mathrm{Re}\left[\dfrac{1}{\Sigma_1-\Sigma_2}\left(p_2\eta_2 - p_1\eta_1 \right) \right] \\ v = K_I\sqrt{\dfrac{2r}{\pi}} \mathrm{Re}\left[\dfrac{1}{\Sigma_1-\Sigma_2}\left(\Sigma_1 q_2\eta_2 - \Sigma_2 q_1\eta_1 \right) \right] \\ \qquad + K_{II}\sqrt{\dfrac{2r}{\pi}} \mathrm{Re}\left[\dfrac{1}{\Sigma_1-\Sigma_2}\left(q_2\eta_2 - q_1\eta_1 \right) \right] \end{cases} \quad (5)$$

where,

$$\begin{cases} p_i = a_{11}^{'}\Sigma_i^2 + a_{12}^{'} - a_{16}^{'}\Sigma_i \\ q_i = a_{12}^{'}\Sigma_i + \dfrac{a_{22}^{'}}{\Sigma_i} - a_{26}^{'} \end{cases}, \quad i = 1, 2 \quad (6)$$

$$\eta_i = \sqrt{\cos\theta + \Sigma_i \sin\theta} \quad (7)$$

The relationships between a_{ij} and $a_{ij}^{'}$ are

$$a_{11}^{'} = a_{11}\cos^4\psi + (2a_{12}+a_{66})\sin^2\psi\cos^2\psi + a_{22}\sin^4\psi \quad (8)$$

$$a_{22}^{'} = a_{11}\sin^4\psi + (2a_{12}+a_{66})\sin^2\psi\cos^2\psi + a_{22}\cos^4\psi \quad (9)$$

$$a_{12}^{'} = a_{12} + (a_{11}+a_{22}-2a_{12}-a_{66}) \times\sin^2\psi\cos^2\psi \quad (10)$$

$$a_{66}^{'} = a_{66} + 4(a_{11}+a_{22}-2a_{12}-a_{66}) \times\sin^2\psi\cos^2\psi \quad (11)$$

$$a_{16}^{'} = \begin{bmatrix} a_{11}\cos^2\psi - a_{22}\sin^2\psi \\ -(2a_{12}+a_{66})\cos 2\psi/2 \end{bmatrix} \sin 2\psi \quad (12)$$

$$a_{26}^{'} = \begin{bmatrix} a_{11}\sin^2\psi - a_{22}\cos^2\psi + \\ (2a_{12}+a_{66})\cos 2\psi/2 \end{bmatrix} \sin 2\psi \quad (13)$$

where $a_{ij}^{'}$ is the flexibility coefficient under the local coordinate system *x*-*O*-*y*; K_I is Mode I stress intensity factor, MPa·m$^{0.5}$; K_{II} is Mode II stress intensity factor, MPa·m$^{0.5}$; ψ is the included angle of material main direction 1 and *x* axis, degree; Σ_i is the material characteristic parameter related to coordinate system, i=1, 2.

Known from eq. (1) that: (1) The same as for an isotropic material, the crack tip stress in the anisotropic material has the singularity of $r^{-\frac{1}{2}}$ on the condition of $r \to 0$, and stress field strength is also determined by the stress intensity factor. (2) The distribution of stress and the displacement field depend not only on θ, but also relate to the elastic coefficient of the anisotropic material. For the anisotropic material, the anisotropy not only influences the distribution of stress and displacement, but also the intensity of stress field and displacement field, which means they affect the value of the stress intensity factor. The stress intensity factor can be expressed by fracture toughness which reflects the crack instability and propagation ability[21].

The stratum tends to develop shear fracture along initial fissure under the condition of certain formation characteristics (initial fissure, distribution characteristic and stress state), especially when the difference between maximum and minimum in-situ stress is large, the angle between initial fissure and principal stress is about 30-60 ° and low viscosity fluid is injected. Even if a shear fracture appears first, the tension fractures along the fracture plane are still mainly formed during the fracture propagation. The unstable propagation of tensile cracks mainly occurs in the matrix. Therefore, we assume the hydraulic fracture extension is mainly the unstable propagation of a type I crack to discuss the hydraulic fracture propagation rules in CBM reservoirs. The fracture toughness of type I cracks only is considered to study its anisotropy in a coal seam.

Three point bending tests

From the previous analysis, the critical values of Mode I stress intensity factor are the fracture toughness of principal directions 1 and 2 when ψ is 0° and 90° respectively. In direction 1 along and direction 2 perpendiculars to bedding respectively, the corresponding fracture toughness values can be obtained by three point bending tests.

Sample preparation

All the coal samples are taken from the Shanxi group II_1 coal seam in Jiaozuo coal mine of Henan province, China. The coal seam is very thick (the average thickness is about 9 m), and has simple structure and distributional stability. Its depth is about -1070 m to -1080 m.

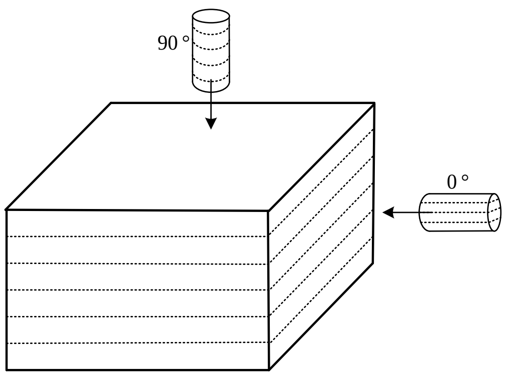


Figure 2. Directional coring schematic diagram.

To study the influence of bedding on coal fracture toughness and predict the micro fractures propagation process, we carried out three point bending tests. Because of the anisotropy of the coal, the angles between drilling direction and bedding plane have been selected as 0° and 90°. Figure 2 is a schematic diagram of the directional coring. The dashed line indicates bedding.

The cylindrical specimens used in the tests have the diameter and height of 50 mm and 200 mm respectively. For the specimen notch we adopt a longitudinal notch form. Its depth and width are 20 mm and 1.5 mm, respectively [22].

Experimental method

A multi-functional rock testing system (RMT) is used to carry out three points bending tests on raw coal specimens with different bedding angles. The samples are divided into two groups based on the relative location of bedding and notch plane. In one group the notch plane is perpendicular to the bedding, and in the other group the notch plane is parallel to the bedding. Each condition of test is performed on at least three samples, and the average of the test result is taken.

Test results

The fracture toughness is given by[23]

$$K_{IC} = 0.25\left(\frac{S_d}{D}\right)\frac{P_{max}}{D^{1.5}}\,y\left(\frac{a}{D}\right) \quad (14)$$

$$y\left(\frac{a}{D}\right) = \frac{12.75\left(\frac{a}{D}\right)^{0.5}\left[1+19.65\left(\frac{a}{D}\right)^{4.5}\right]^{0.5}}{\left(1-\frac{a}{D}\right)^{0.25}} \quad (15)$$

where K_{IC} is the fracture toughness, MPa·m$^{0.5}$; S_d is the distance between the two supporting points, which is 160 mm during the tests; D stands for the specimen diameter, mm; P_{max} is the peak load, N; a is the notch depth, mm.

From the eq. (14) and eq. (15), fracture toughness depends only on the sample dimensions, notch geometry and failure load. Based on the calculation formulas, three point bending test results are listed in Table 1.

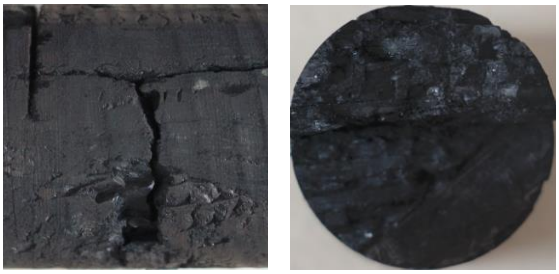
Table 1. Three point bending test results.

The relative position of notch plane and bedding	Notch depth /mm	Notch width /mm	Diameter /mm	Peak load /N	Fracture toughness /MPa·$m^{0.5}$	Average value /MPa·$m^{0.5}$
Perpendicular	18.92	1.58	49.61	562.72	0.409	0.364
	20.73	1.63	49.74	479.43	0.385	
	19.44	1.46	50.38	421.07	0.298	
Parallel	20.38	1.55	50.21	145.90	0.111	0.120
	20.15	1.57	49.82	177.04	0.136	
	19.27	1.66	49.65	151.27	0.112	

Table 1 shows that fracture toughness is the largest (0.364 MPa·$m^{0.5}$) when the notch plane is perpendicular to the bedding, which means that the matrix has the maximum fracture toughness. The minimum fracture toughness is 0.120 MPa·$m^{0.5}$, when the notch plane is parallel to the bedding, which reveals that bedding is a weak interface. The former is about three times of the latter, which fully reflects the anisotropy of coal fracture toughness. Based on above test results, bedding has a weak ability to prevent fracture initiation and propagation. If a hydraulic fracture extends perpendicular to the bedding, it is extremely likely to have bifurcation and diversion at the bedding.

Anisotropy analysis of three point bending failure

Figure 3 shows three point bending typical fracture styles for different orientations of notch plane and bedding. Coal specimens rupture mode basically shows two types of failure: (1) Notch plane perpendicular to bedding. The fracture does not initiate at the tip of the notch. Instead it initiates along the bedding, near the notch tip. The fracture propagates along the bedding under the action of the applied load. A vertical diversion produces the secondary fracture, which propagates approximatively parallel to the direction of notch depth. Ultimately, the broken sample contains two approximately vertical fractures. (2) Notch plane parallel to bedding. The fracture initiates at the tip of the notch and propagates along the prefabricated crack until complete break. It shows no deviation of fracture path. The failure sample forms a straight extension path, and the specimen breaks into two approximately equal parts. The fracture surface is the coal bedding, which is flat and smooth.



(i) Extension path **(ii) Fracture surface**

(a)

(i) Extension path **(ii) Fracture surface**

(b)

Figure 3. Fracture patterns of three point bending tests. ***a***, Notch perpendicular to bedding. ***b***, Notch parallel to bedding.

The main reason that causes the anisotropy of coal rock fracture toughness is the anisotropy of the toughening effect. For layered sedimentary rock, the main toughening mechanisms throughout the fracturing process are bedding cracking, fracture path deviation and delamination peeling. When the notch is perpendicular to the bedding, bedding cracking and fracture path deviation are the reasons why fracture toughness has the maximum value during fracture propagation. When the notch is parallel to the bedding, the fracture propagates along bedding, which has no toughening mechanism. The bonding strength of bedding is low. Bedding has weak ability to prevent fracture extension, so fracture toughness has the minimum value.

Micro-fracture propagation during hydraulic fracturing

A geological geomechanical model used to predict the propagation of fractures during hydraulic fracturing is built by finite element software RFPA (Realistic Failure Process Analysis)[16]. The model is used to study the propagation rules of the cracks and the influence of bedding on the fracture network. Parameters used in the numerical simulation are based on the test results. The results can provide a reference basis for the fracture propagation rule and the geometry of fracture networks of CBM reservoirs during hydraulic fracturing.

Basic parameters

To ensure the input parameters of the numerical model truly represent the actual formation, the average values of coal rock matrix and bedding determined in the laboratory tests are used. Table 2 lists the mechanical parameters of matrix and bedding.

According to the geological data, the angle between the bedding and the horizontal plane is 18-35°. To simplify the calculation, the angle is valued as 30° in the numerical simulations. The hydraulic pressure is increased at a rate of 0.1 MPa by single steps until the stratum ruptures completely to form a number of hydraulic fracture channels. The fracturing fluid is water with the density and the injection rate of 1000 kg/m^3 and 0.5 ml/s, respectively.

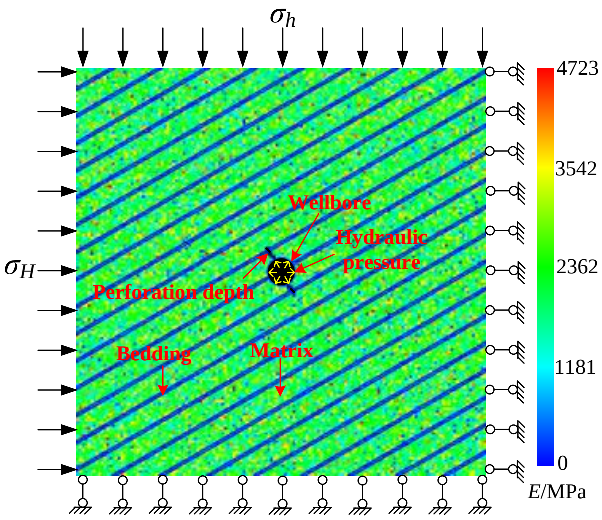


Figure 4. Two dimensional plane strain model (*E* is elasticity modulus).

Taking the cross section perpendicular to the wellbore as the research object, the calculation model of a well with perforation completion is established. The numerical model and its boundaries are shown in Figure 4. The model is a square with a side length of 10 m, and the wellbore diameter is about 0.2 m. The distance between the wellbore and the boundary is more than 10 times larger than the wellbore diameter, which could effectively reduce the boundary effect on the calculation results. There are 300×300 elements in the model, and the perforation depth is 150 mm, perpendicular to the bedding. The horizontal in-situ stresses are applied on two sides of the model, and the displacement boundary is applied on the other two sides. The matrix and bedding are parallel and they alternate. The matrix is with a lighter color and wider range, while the bedding has darker color and narrower scope, as also marked in Figure 4. To reflect the actual characteristics of coal rock, the elasticity modulus of the model is not a fixed value to consider the influence of randomness.

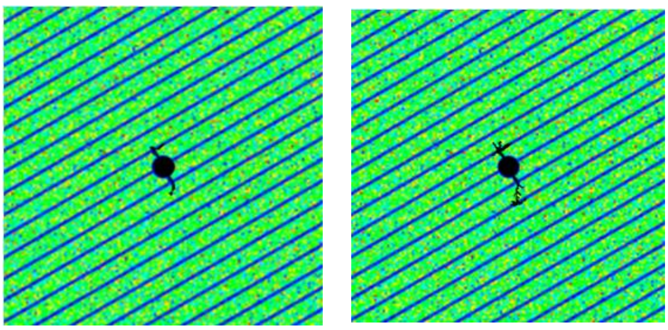
Table 2 Parameters used in the simulation model.

Items	Unit	Matrix	Bedding
Poisson's ratio		0.31	0.34
Internal friction angle	degree	18.8	16.3
Elasticity modulus	GPa	1.93	0.65
Tensile strength	MPa	1.17	0.27
Cohesive strength	MPa	0.82	0.19
Permeability	mD	0.154	1.644
Porosity	%	4.8	3.8
Compressive strength	MPa	11.88	3.06
Fracture toughness	$MPa \cdot m^{0.5}$	0.364	0.12
Vertical stress	MPa	23.4	
Maximum horizontal stress	MPa	25.7	
Minimum horizontal stress	MPa	16.7	

Result analysis

The crack propagation in the CBM reservoir during hydraulic fracturing is shown in Figure 5. With the fracturing fluid being injected into the formation continuously, the hydraulic fracturing cracks at both ends of the perforated interval and the fracture extends along the perforation direction (Figure 5(a)). When the fracture extends to the bedding, bifurcation and diversion of the hydraulic fracture take place because of the low strength and high permeability of bedding. The induced fractures are produced along the bedding, while the major fracture still extends perpendicularly to the bedding, but with much lower fracture propagation speed (Figure 5(b)).

After the induced fracture propagates for a certain distance along the bedding, the fracturing fluid cannot maintain the rapid extension of the cracks because of the high leak-off and the energy consumed by the friction between the induced crack surfaces. So a new secondary fracturing crack forms along another bedding. The newly formed crack cannot stop the continuous extension of the major fracture and the original secondary fractures completely but reduces their extension speed (Figure 5(c)). Ultimately, the complex hydraulic crack network is formed which prevents the fast propagation of hydraulic fractures. Increasing the injection rate is the only way to ensure the continuous and rapid extension of major and secondary fractures to form a more complicated fracture network (Figure 5(d)).



(a) **(b)**

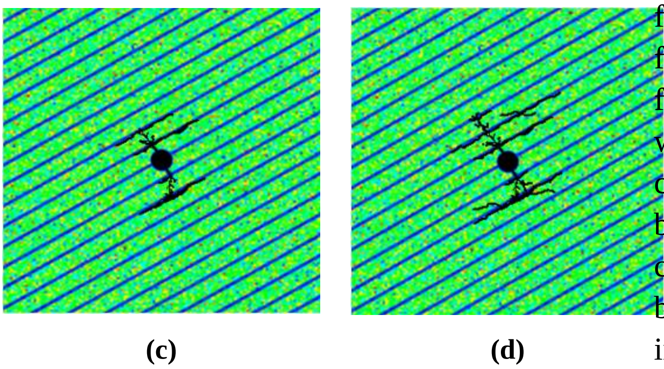


Figure 5. Hydraulic fractures evolution diagram at different injection pressures. ***a***, 2.6 MPa. ***b***, 2.8 MPa. ***c***, 3.0 MPa. ***d***, 3.2 MPa.

The effect of bedding fracture toughness on fracture propagation

To investigate the effects of the fracture toughness of bedding on the hydraulic fracture, the fracture toughness of bedding is taken as 0.05, 0.10, 0.15 and 0.20 MPa·m$^{0.5}$ respectively while that of the matrix is set as 0.364 MPa·m$^{0.5}$. The other parameters used in the simulations are as listed in Table 2. The hydraulic fracture propagation geometry is shown in Figure 6.

As shown in Figure 6, the fracture toughness of bedding has great influence on hydraulic fracture geometry. When the fracture toughness of bedding is larger, the hydraulic fracture is more likely to propagate perpendicular to the bedding, and the major fracture has bifurcation and diversion many times at the bedding to form multiple secondary fractures extending along the bedding. With a decrease of the bedding fracture toughness, the number of times of bifurcation and diversion at the bedding decreases, while the number of secondary fractures also gradually reduces. However, the propagation distance of secondary fractures along the bedding increases gradually. This suggests that the hydraulic fracture tends to propagate perpendicularly to the bedding, and has bifurcation and diversion to form complex fracture geometries on the condition of large fracture toughness of bedding. The secondary fracture tends to propagate along the bedding with simple fracture geometry on the condition of small fracture toughness of bedding. Therefore, the hydraulic fracturing crack is likely to bifurcate and swerve at the bedding to form multiple secondary fractures in the coal seam with larger bedding fracture toughness, which is beneficial to form a fracture network.

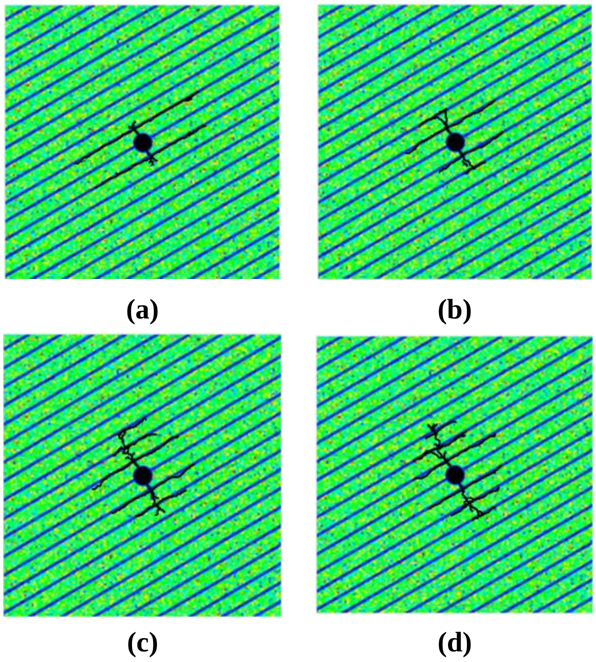


Figure 6. Hydraulic fracture morphology for different bedding fracture toughnesses. ***a***, 0.05 MPa·m$^{0.5}$. ***b***, 0.1 MPa·m$^{0.5}$. ***c***, 0.15 MPa·m$^{0.5}$. ***d***, 0.2 MPa·m$^{0.5}$.

Summary and conclusions

(1) The material anisotropy not only influences the distribution of stress and displacement at a crack tip, but also affects the intensities of stress field and displacement field, which are both determined by stress intensity factor and elastic constants.

(2) The fracture toughness of coal shows strong anisotropic characteristics at different bedding angles during three point bending

tests. Bedding has a weak ability to prevent fracture initiation and propagation. The specimen rupture modes basically show two failure types.

(3) The hydraulic fracture initiates at the end of the perforation due to tension fracturing, and it generates induced fractures at the bedding. The bifurcation and diversion of major fractures take place at the bedding during the further extension. More newly induced fractures are formed, creating a complicated fracture network which achieves the purpose of CBM reservoir fracturing treatment.

(4) The fracture toughness of bedding has great influence on hydraulic fracture geometry. The fracture is likely to bifurcate and swerve at the bedding to form multiple secondary fractures with larger bedding fracture toughness, which is beneficial to form a fracture network.

Acknowledgement

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