Cracking Mechanism and Numerical Simulation of Fractional Hydraulic Fracturing Cracks

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Abstract: Gas extraction is the fundamental way to control the gas disaster in coal mine. The segmented hydraulic fracturing technology can effectively solve the problem of stress concentration caused by conventional fracturing by implementing the measures of gas extraction hole and fracturing hole, and achieve the purpose of uniform pressure discharge of coal seam. This paper analyzes the expansion characteristics of small-scale hydraulic fracturing fracture and its penetration mechanism, It is concluded that the expansion of coal seam crack in hydraulic fracturing can be divided into preparation stage, crack generation stage and crack extension stage; The induced stress between the fractures can change the stress field of the formation, To create a stress superposition between the holes, Promote intra-seam steering of inter-hole cracks, When the gas extraction hole is arranged in coordination with the fracturing hole, Can connect the fracturing crack and the extraction hole fracture area, Form a whole pressure relief network; A numerical model of fractional hydraulic fracturing is developed, The extension law of fracturing crack and the change law of coal stress are simulated. The study shows that segmented fracturing can effectively solve the problem of stress concentration after conventional fracturing, to achieve the purpose of uniform pressure discharge of coal seam, but also can make the fracturing crack evenly expanded to both sides, so that the coal in the fracturing area is in a uniform pressure discharge state.

Keywords: extraction drilling; segment fracturing; stress field; hydraulic crack

Introduction

Most of the coal mines in China belong to high gas and low permeability mines [5], Among them, low permeability seam accounts for more than 95% of high gas mines and outburst mines, The permeability coefficient of coal seam is only 10^{-3}~10^{-4}mD, That is, 0.04~0.004m^2/(MPa^2·d), The air permeability coefficient is less than 0.14m^2/ (MPa^2·d), The its and pores of the coal seam are poorly developed, Low permeability of the coal seam, Conventional hole hole gas extraction radius is small, Low extraction drilling concentration, fast flow attenuation, Long extraction standard time, Poor extraction effect, If no additional penetration measures are taken, It is difficult to achieve coal seam elimination in a short time, To achieve the purpose of safe production, For this reason, extraction is often carried out at the cost of dense holes and coal seam roof roadway and other high engineering investment, Lack of effective coal seam disturbance pressure discharge penetration technology, Cannot effectively solve the problem of efficient gas extraction, Directly cause the low mine gas extraction rate, The proportion of "pumping, mining and digging" is unbalanced.

Segmental fracturing is a technique that separates different layers of the reservoir by blocking ball or flow limiting technology, which can segment fracturing at different positions in the same well according to the characteristics of the reservoir. The main operation methods are continuous tubing fracturing and sleeve packer fracturing. Multistage fracturing technology is the main technology for reservoir hydraulic fracturing. 85% of American shale gas production Wells use the combination of horizontal Wells and multistage fracturing technology, which increases production significantly. Multistage fracturing has high yield efficiency and mature technology, which is suitable for Wells with more production layers and long horizontal Wells. For reservoirs with large differences in air content in different layers, multistage fracturing can make full use of the gas content characteristics of reservoirs to optimize the fracturing level.

I. Starting Mechanism of Stage Hydraulic Fracturing Crack

I.1 Stress field distribution of primary crack induction

When the fracturing of the long borehole is segmented, the crack form is the transverse crack perpendicular to the direction of the borehole. Therefore, the study of the induced stress field generated after the formation of the crack-induced stress geometry model is established on the basis of the homogeneous and isotropic two-dimensional plane strain model. The model assumes that the fracture form is the vertical joint, the longitudinal profile of the crack is oval, the height of the half joint is H/2, the height of the fracture is the y-axis, and the vertical direction is the x-axis of the hydraulic crack (long drilling direction) to establish the hydraulic fracture induced stress field geometry model in Figure 1. Tension stress is defined as positive and compressive stress as negative.

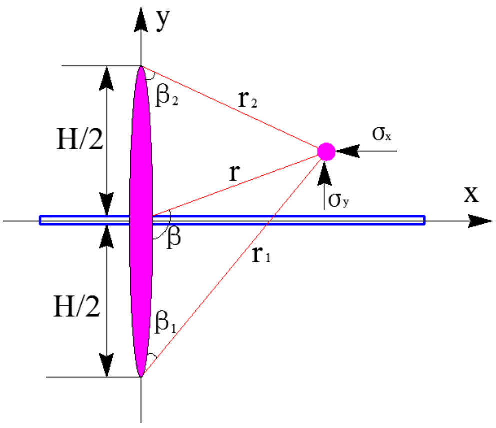


Figure1. Geometric model of the hydraulic fracture-induced stress field

The induced positive stress and shear stress generated by the first crack at a certain particle point (x, y, z) around the long borehole are:

$$\begin{cases} \sigma_{x诱导} = -p\dfrac{r}{c}\left(\dfrac{c^2}{r_1 r_2}\right)^{3/2}\sin\beta\sin\dfrac{3}{2}(\beta_1+\beta_2) - p\left[\dfrac{r}{(r_1 r_2)^{1/2}}\cos(\beta-\dfrac{1}{2}\beta_1-\dfrac{1}{2}\beta_2)-1\right] \\ \sigma_{y诱导} = p\dfrac{r}{c}\left(\dfrac{c^2}{r_1 r_2}\right)^{3/2}\sin\beta\sin\dfrac{3}{2}(\beta_1+\beta_2) - p\left[\dfrac{r}{(r_1 r_2)^{1/2}}\cos(\beta-\dfrac{1}{2}\beta_1-\dfrac{1}{2}\beta_2)-1\right] \\ \sigma_{z诱导} = \nu(\sigma_{x诱导}+\sigma_{y诱导}) \\ \tau_{y诱导} = -p\dfrac{r}{c}\left(\dfrac{c^2}{r_1 r_2}\right)^{3/2}\sin\beta\cos\dfrac{3}{2}(\beta_1+\beta_2) \end{cases} \quad (1)$$

among, $c = H/2; r = \sqrt{x^2+y^2}; r_1 = \sqrt{x^2+(y+c)^2}; r_2 = \sqrt{x^2+(y-c)^2};$

$$\beta = \tan^{-1}(-x/y); \beta_1 = \tan^{-1}[x/(-y-c)]; \beta_2 = \tan^{-1}[x/(c-y)];$$

I.2 Study on the ground stress distribution around the long borehole

Research on the ground stress distribution around the long borehole, the original formation stress system is mainly composed of σ_V three mutually vertical stresses, respectively σ_H : the vertical σ_h overlying formation stress, the maximum horizontal main stress in the horizontal direction and the minimum horizontal main stress. A schematic diagram of the distribution of the original and induced stress fields is shown in Fig.2.

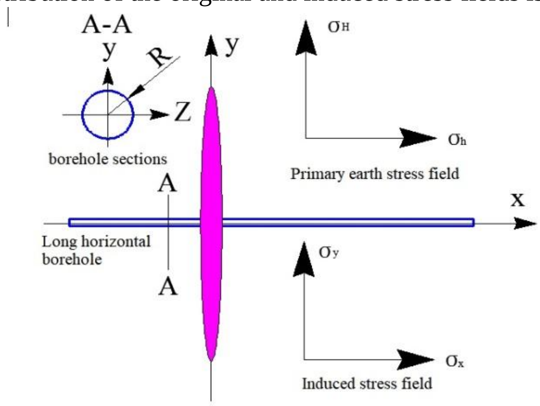


Figure2. Ground stress distribution under the initial crack-induced stress

The superposition of the induced stress field and the original stress field in Figure 2 can obtain the composite stress field under the initial fracture condition. According to the superposition principle, the mathematical model of the composite stress field is as follows:

$$\begin{cases} \sigma_H^{'} = \sigma_{\mathrm{H}} + \nu(\sigma_{x诱导} + \sigma_{y诱导}) \\ \sigma_h^{'} = \sigma_h + \sigma_{x诱导} \\ \sigma_v^{'} = \sigma_v + \sigma_{y诱导} \end{cases} \tag{2}$$

Establish a coordinate system perpendicular to the long drilling section on the horizontal section, and analyze the stress distribution at the drilling wall.

(1) Stress component caused by the internal pressure of the long borehole

During the fracturing operation, the fracturing fluid will produce internal pressure on the formation near the well wall and cause a change in the stress at the well wall. Under the coordinate system of the drilling wall, the stress component caused by the internal pressure of the wellbore is

$$\begin{cases} \sigma_r = -p_w \\ \sigma_\theta = p_w \\ \sigma_z = bp_w \end{cases} \tag{3}$$

(2) Stress component caused by compound stress

Three composite $\sigma_v^{'}$ stress $\sigma_h^{'}$ $\sigma_H^{'}$ and will generate stress components on the well wall, and the stress components on the drilling wall are:

$$\begin{cases} \sigma_r = 0 \\ \sigma_\theta = \sigma_v^{'} + \sigma_H^{'} - 2(\sigma_v^{'} - \sigma_H^{'})\cos 2\theta \\ \sigma_z = \sigma_h^{'} - 2\upsilon(\sigma_v^{'} - \sigma_H^{'})\cos 2\theta \\ \tau_{r\theta} = \tau_{rz} = \tau_{\theta z} = 0 \end{cases} \tag{4}$$

(3) Stress component caused by the fracturing fluid seepage effect

During fracturing operations, the stress components generated due to the loss of fracturing fluid to the formation are:

$$\begin{cases} \sigma_r = \delta\phi(p_w - p_0) \\ \sigma_\theta = -\dfrac{\delta\alpha(1-2\nu)}{1-\upsilon}(p_w - p_0) + \delta\phi(p_w - p_0) \\ \sigma_z = -\dfrac{\delta\alpha(1-2\nu)}{1-\upsilon}(p_w - p_0) + \delta\phi(p_w - p_0) \end{cases} \tag{5}$$

Using the superposition principle, the well wall stress field model under the combined action of well bore internal pressure, composite stress field and fracture seepage effect is considered:

$$(\begin{cases} \sigma_r = -p_w + \delta\phi(p_w - p_0) \\ \sigma_\theta = p_w - \sigma_v^{'} + 3\sigma_H^{'} - 2\sigma_H^{'}\sin 2\theta - \dfrac{\delta\alpha(1-2\nu)}{1-\nu}(p_w - p_0) + \delta\phi(p_w - p_0) \\ \sigma_z = bp_w + \sigma_h^{'} - 2\nu(\sigma_v^{'} - \sigma_H^{'})\cos 2\theta - \dfrac{\delta\alpha(1-2\nu)}{1-\nu}(p_w - p_0) + \delta\phi(p_w - p_0) \\ \tau_{r\theta} = \tau_{rz} = \tau_{\theta z} = 0 \end{cases} \tag{6}$$

(4) Analysis of crack initiation in the induced stress field

During the process of hydraulic fracturing, the rock cracking is mainly tensile fracture. According to the rock tensile rupture criteria, when the effective tensile stress of the rock reaches the tensile strength of the rock, the rock material will $z-\theta$ break. If the original microcracks or microcracks exist in the drilling wall rock, the tensile strength of the rock is 0. The maximum effective tensile stress on the plane of the well wall is the maximum main stress minus the rock plane, and when it is equal to or greater than the rock tensile strength, the rock at the drilling wall begins to fracture, i. e

$$\sigma_z - \eta p_0 \geq \sigma_t \tag{7}$$

When the equal sign is established, it is the minimum rupture pressure required for the crack crack. Hypothesis: q= 0°, the long borehole is arranged along the minimum main stress direction, and the drilling wall stress field model is:

$$(\begin{cases} \sigma_r = -p_w + \delta\phi(p_w - p_0) \\ \sigma_\theta = p_w - \sigma_v^{'} + 3\sigma_H^{'} - 2\sigma_H^{'}\sin 2\theta - \dfrac{\delta\alpha(1-2\nu)}{1-\nu}(p_w - p_0) + \delta\phi(p_w - p_0) \\ \sigma_z = bp_w + \sigma_h^{'} - 2\nu(\sigma_v^{'} - \sigma_H^{'})\cos 2\theta - \dfrac{\delta\alpha(1-2\nu)}{1-\nu}(p_w - p_0) + \delta\phi(p_w - p_0) \\ \tau_{r\theta} = \tau_{rz} = \tau_{\theta z} = 0 \end{cases} \tag{8}$$

Order $k = \left[\dfrac{\delta\alpha(1-2\upsilon)}{1-\upsilon} - \delta\phi\right]$, the crack rupture pressure p_{wp} can be obtained:

$$p_{wp} = \frac{\sigma_h^{'} - 2\nu(\sigma_v^{'} - \sigma_H^{'})\cos 2\theta + (k-\eta)p_0 - \sigma_t}{k-b} \tag{9}$$

II. Subsection Hydraulic Fracturing Fracture Simulation

II. 1 Simulation and Modeling

To investigate the length of hydraulic fracturing hole, it were simulated using RFPA2D-Flow numerical simulation software. Since underground fracturing is performed step by step, when one section of fracturing is completed, another section is done, it is difficult to determine how large the scale of the first segment is, and what impact on the second section. Therefore, in the modeling, the crack and stress of the two segments of hydraulic fracturing are investigated at the same time, so as to analyze the segment spacing and the fracturing situation of each segment to determine the length of the segment.

The geometric model is established as follows: the model size is 100m 6m, the thickness of the simulated coal seam is set to 2.8m, the diameter of the fracturing drilling hole is 94mm, divided into 1000120 a total of 120000 grids. Two-dimensional plane strain analysis was applied, with the Moore-Culoulb criterion and the Weber distribution (Figure 3). Load boundary is: vertical load of 10MPa at the top, gravity by equivalent coal layer; lateral horizontal load, horizontal stress of 12MPa. The water injection pressure increases with a step size of 0.5MPa / step. After the fracturing, the coal stress data on the white dotted line can be extracted to study the stress distribution characteristics on the line. Model mechanical parameter settings are provided in Table 1.

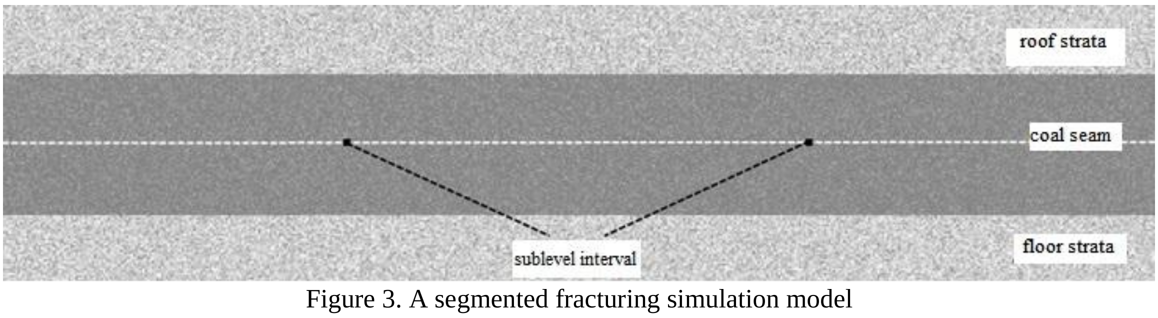


Figure 3. A segmented fracturing simulation model

Table 1 Model parameters

The parameter name	Rock layer 1,3	coal rake
Homogeneity m	3	3
compression strength f_c /MPa	40	17
modulus of elasticity E_0 /GPa	35	6
Poisson ratio v	0.25	0.3
tensile strength f_t /MPa	4	2
Penetration coefficient k_0 / (m / d)	0.01	0.1
pore pressure parameter α	0.3	0.4
porosity n	0.2	0.4

II.2 Simulation Study of Segment Spacing

The smaller the segment spacing of long drilling, although the interaction between fracturing cracks is enhanced, the overall fracture network bandwidth decreases, which undoubtedly increases the workload of fracturing, time-consuming and laborious; if the segment spacing is too large, the interaction between the cracks is weakened, resulting in inadequate transverse direction, reducing the density of joint network, and easy to form blank belt, affecting the gas control effect and endangering the safety of mine production.

Therefore, a reasonable segment spacing is of great significance for the effective hydraulic fracturing of long drilling segments. Based on previous hydraulic fracturing experience, this project conducted a simulation study of 40m, 35m, 30m and 25m.

Fig.4 shows the influence on fracturing fracture expansion and head distribution when the segment spacing d is 25, 30, 35 and 40m, respectively. When the segment spacing d is 25 and 30m, due to the close segment spacing, the stress superposition effect is obvious, the micro-cracks and macro cracks in the coal between the holes are effectively opened, the cracks between the holes are basically through, the fracturing fluid forms a flow channel in the meantime, and the pressure discharge and penetration effect of the coal between the holes is obvious. Compared with the segment spacing of 25m, the segment spacing of 30m increases the fracturing volume of the coal seam, and the penetration effect between the two segments is not obvious. For the same size area, the segment spacing of 30m can effectively improve the utilization rate of the fracturing equipment, reduce the conversion times of the fracturing equipment, effectively save manpower and material resources, and efficiently develop the area between the segments, leaving no blank zone. When the segment spacing is 35m, The stress superposition effect between segments is weakened, Due to the heterogeneity of the coal body, The left fracturing hole cracks first, The fracturing crack expands to the deep coal, Pressure-generated pressure into these near-field cracks, And interfere with the crack expansion of the right fracturing hole through the form of a stress wave, Which changes the in situ stress field around the right hole, Stress is concentrated around the right fracturing hole, Not only makes it rupture more difficult, And the direction of the fracture expansion becomes uncertain, Interpore cracks cannot penetrate effectively, Presence of a fracturing blank band, Stress concentration here not only fails to produce cracks, It also close the native fissure of the coal seam, Gas output becomes even more difficult, The purpose of pressure relief and penetration increase cannot be achieved. When segment spacing further expanded to 40m, due to the segment spacing is larger, the interaction between two segments and further weakened, is basically equivalent to two separate sections for hydraulic fracturing, due to the heterogeneity of coal seam, crack extension more random, coal destruction between holes is not sufficient, there is a large blank band, through the worst effect. With the increase of the distance between holes, the cracking pressure also increases to different degrees. Reasonable selection of segment spacing can not only effectively solve the stress concentration in the process of heterogeneous coal seam segment fracturing, but also realize the downhole hydraulic fracturing increase operation under relatively low pressure.

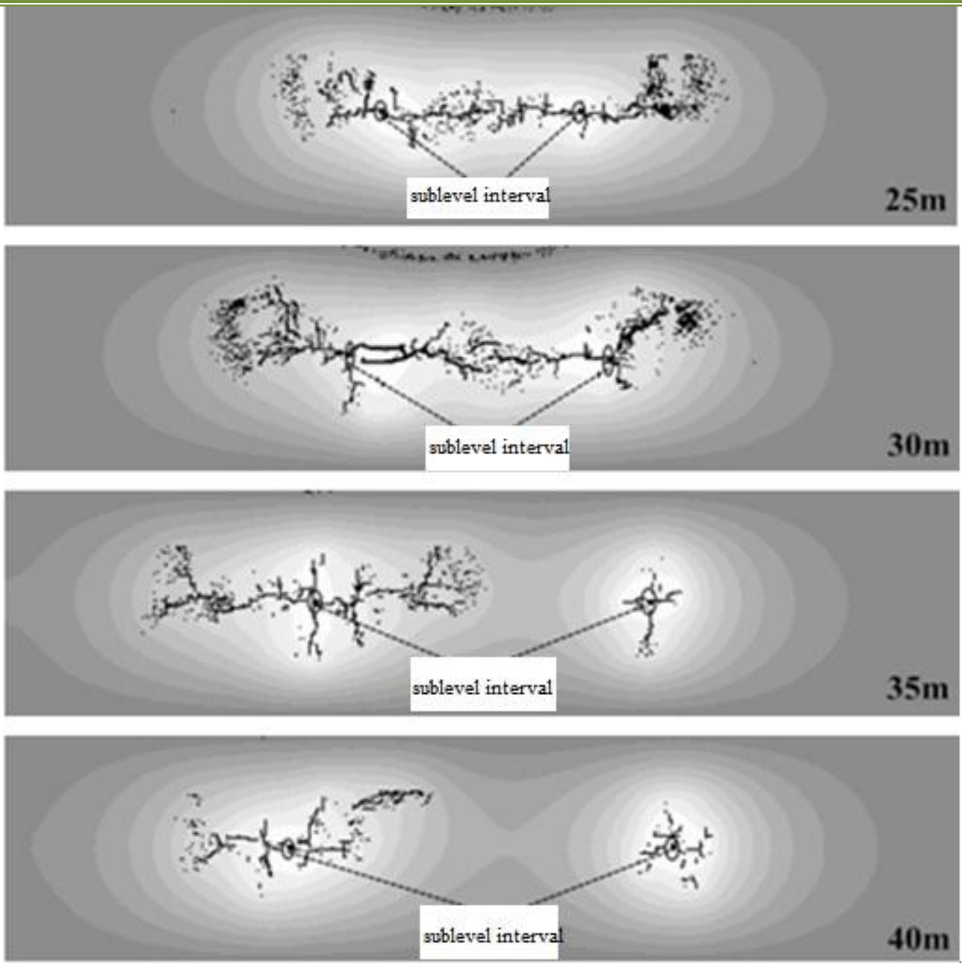


Figure 4. Fracking fracture expansion state at different segment spacing

Fig.5 shows the damage of coal in the process of 25m, 30m, 35m and 40m). With the increase of the segment spacing, the stress superposition of the coal between the two segments gradually weakens, the coal rupture becomes more and more difficult, and the development degree of the crack between the segments gradually weakens. When the segment spacing is 25m, Due to the intersegment stress superposition effect, The coal is fully damaged, The fissure network develops relatively well in the intervening period, Coal body pressure discharge is more sufficient, The effect of coal penetration between segments is obvious; When the segment spacing is 3 m, Higher development of the intersegmented fissure network, And the segmented lateral fissure is also fully developed, The coal body in the inside and outside of the section have a good pressure discharge effect; As the segment spacing continues to expand, When the segment spacing reaches 35m, Due to the heterogeneity of the coal seams, Different order of split, The left fracturing section with good fracture expansion, Strong interference with the crack extension of the right fracturing section, The section fracturing fissure cannot penetrate, Inadequate destruction of the coal body, There are certain blank zones and stress concentration zone, The effect of coal penetration is poor; When the segment spacing is further expanded to 40m, The coal area damage between the two sections is more inadequate, The existence of large blank bands and stress concentration zones, The effect of coal penetration between segments is worse.

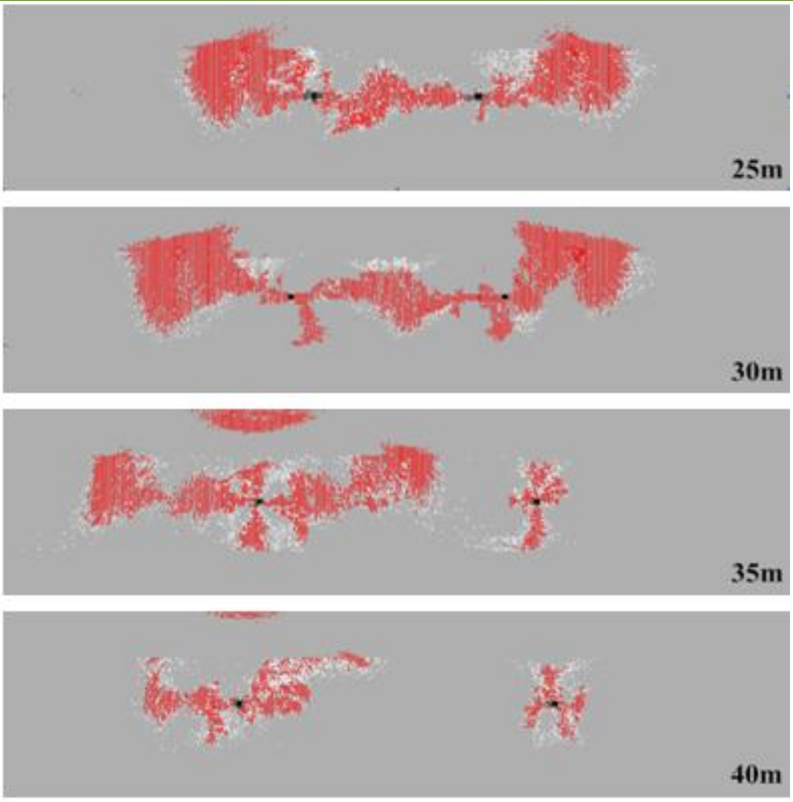


Figure 5. Distribution of fracturing failure areas at different segment spacing

According to the comparison and analysis of the results, we must choose a reasonable spacing of water injection holes. If the segment spacing is remote, the interaction between the segments is small, the seam crack and crack extension will be the same as the single segment fracturing effect, and the area of stress concentration forms the large cracking pressure and the unexpected crack extension direction; if the split spacing is too small, although the influence of the pressure relief range is enhanced, and the fracturing construction efficiency is low, and the area between the segments cannot be developed efficiently. Therefore, the reasonable section spacing is 25~30m, which can ensure the full pressure discharge between the sections, so as to realize the purpose of uniform pressure discharge and penetration increase of the coal seam.

III. Analysis of Fracturing Crack Expansion Process and Penetration Enhancement Characteristics

Figure 6 shows the initiation, extension, penetration and macroscopic fracture formation of fracturing cracks when the segment spacing d is 25~30m. The initial water injection pressure is set to 0. When the water injection pressure is less than 15.5MPa, the fracturing fluid is mainly filled in the original crack of the coal body, accompanied by the opening of some microcracks around the hole. At this time, the segment spacing is large, and the two segments have basically no effect in the process of water injection, which is equivalent to two independent holes in the fracturing operation. When the water pressure increases to 15.5MPa, the small cracks around the water injection hole are further developed, and the coal seam breaks up and extends to the depth of the coal body. The fracturing of the two segments begins to influence each other, and the local areas between the segments produce stress superposition. When the water injection pressure further increased to 16.7MPa, coal began to appear large macro cracks, and produce a large number of micro cracks, coal seam damage area expand become high water pressure area, seepage channel gradually formed, keep the 16.7MPa pressure unchanged, fracturing cracks will continue to expand, due to the stress superposition between segments, between coal crack development is good, fracturing cracks in segments through form seam network, between coal fully pressure relief, improved permeability, fracturing end.

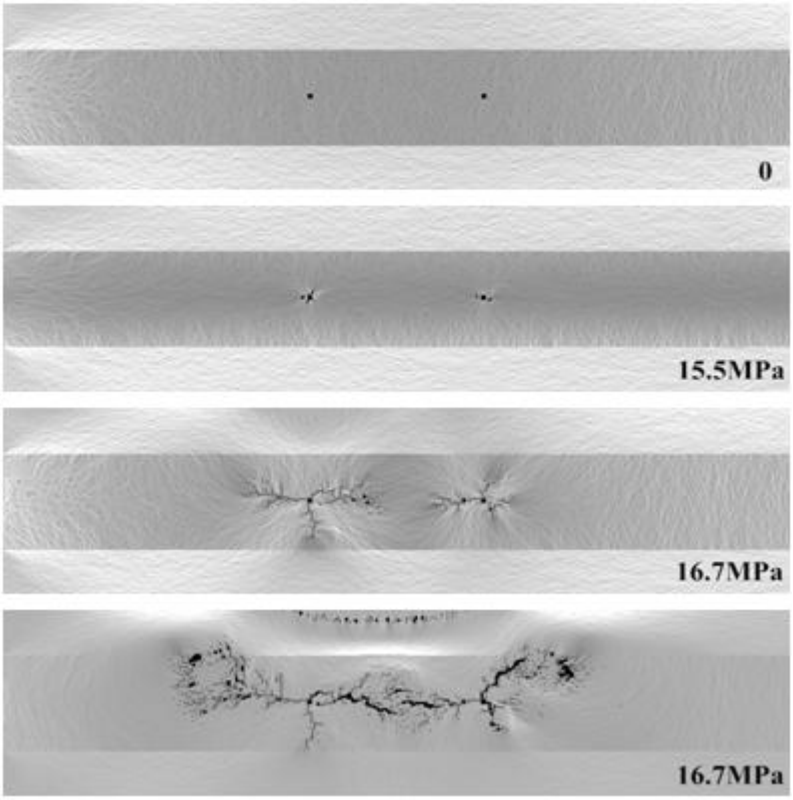
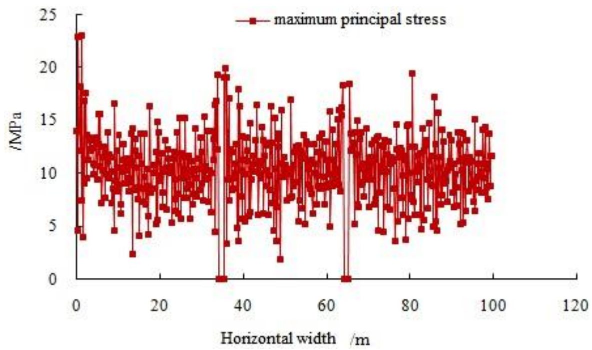
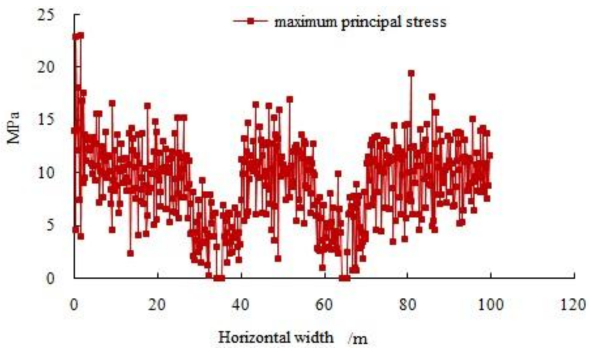


Figure 6. Rule of fracture extension during segment fracturing

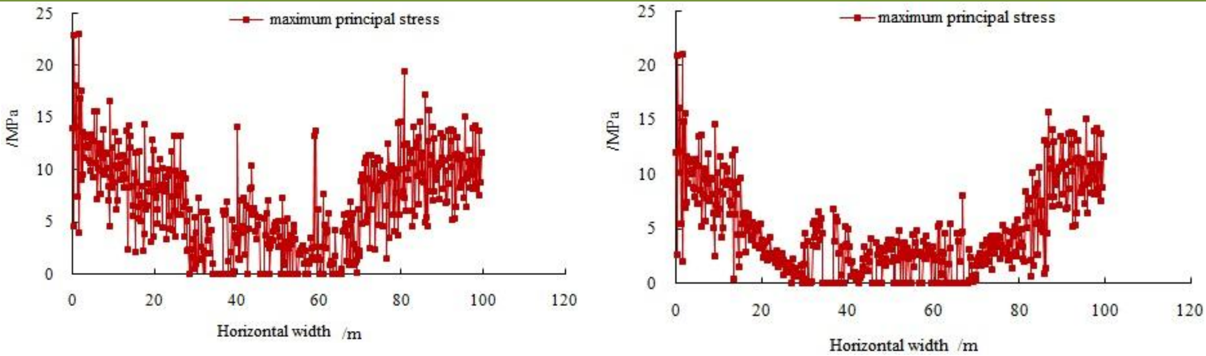
Figure 7 (a) shows the stress distribution of the coal body on the horizontal position of the fracturing long borehole when the water injection pressure is 0. Without fracturing, the coal stress is generally high, with the highest being about 23MPa and the average of about 10MPa. Figure 7 (b) shows that when the water pressure reaches 8MPa, the injected water enters the primary crack of the coal seam, softening the coal body near the segmented outlet hole and the stress is reduced. Figure 7 (c) and (d) show that when the water injection pressure reaches 16.7MPa, the coal body breaks continuously near the section outlet hole, and the stress is gradually reduced. Moreover, the stress superposition in the middle area of the two sections is fully damaged, and the pressure discharge effect is more obvious. The coal seam stress decreases from 10MPa when not fracturing to less than 5MPa. Due to the negative exponential relationship between the permeability coefficient of the coal seam and the seam stress, the seam stress decreases and the permeability is improved. As shown in Figure 7 (d), the coal body within 25~30m between the two holes has been relieved, and the air permeability is bound to be enhanced.



(A) Step 1-1



(B) Step 16-1



(C) Step 33-4 (D) Step 33-30

Figure 7. Dynamic distribution of stress around the hole during segment fracturing

IV. Conclusion

(1) The expansion process, stage characteristics and interinterference of small-scale hydraulic fracturing cracks are analyzed. In the process of multi-point small-scale hydraulic fracturing, the expansion of coal seam cracks can be divided into preparation stage, crack generation stage and crack extension stage. Through the analysis of the interference between the joints, the induced stress generated by multi-point small-scale hydraulic fracturing can change the stress field of the original rock, make the stress superposition between the holes, promote the steering in the cracks between the holes, and improve the penetration effect of the coal between the holes.

(2) The penetration mechanism of multiple small-scale hydraulic fracturing was identified. Multi-point small-scale hydraulic fracturing coal uses the stress disturbance and extraction hole on the guiding action of synchronous fracturing fracture, making the coal in the fracturing area in a uniform pressure relief state, to achieve the purpose of safe production.

(3) The RFPA2D-Flow software is used to simulate the expansion rules of fracturing crack and coal stress change rules under different construction parameters, The results showed that when the synchronous fracturing hole spacing is 30m, Can form large penetrating cracks and microcracks in the interpore coal, They form the seepage channel of pore gas, Easy to produce the gas gas gas, Effectively solve the new stress concentration problems during single-hole fracturing, So that the coal between the holes can be uniformly unloaded; When the coordinated arrangement spacing between the gas extraction hole and the fracturing hole is 4m, Can allow the fracturing crack to expand evenly on both sides, And produce more cracks, Form a disturbance to the coal seam, At the same time, the fracturing fracture and the extraction hole rupture area are connected, Form an integral pressure relief network, Effectively improve the coal seam air permeability, Fracking effect is the best one.

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