Exploration and practice of stress-strain evolution law of hydraulic fracturing in coal mine

Cao Hao*, Zhu Ying, Zhang Jintao
Kunming Institute of Coal Science, Kunming 650200, China

*Corresponding author e-mail: caohao@hpu.edu.cn

Abstract. In order to explore the evolution law of stress and strain in the process of hydraulic fracturing, a hollow inclusions stress-strain gauge was used for monitoring. The results show that the influence range of high-pressure water spreads to the monitoring borehole at 47m after 2 hours of hydraulic fracturing, and its influence on the stress-strain monitoring point reaches the maximum, and the strain tends to be stable in the later stage. After 6 days of hydraulic fracturing, the strain returns to a stable state without any change, but it is still larger than the state before hydraulic fracturing. During hydraulic fracturing, the increment of principal stress increases, but the amplitude is different. Hydraulic fracturing mainly affects the increment of vertical stress, which is related to the stress-strain monitoring point and the space location of the hydraulic fracturing borehole. After hydraulic fracturing, the stress increment decreases gradually and tends to return to the original stable state due to the gradual pressure relief of fracturing fluid, but it is still larger than the state without hydraulic fracturing. Hydraulic fracturing has little effect on the azimuth and dip angle of coal and rock mass. The stress-strain law can provide reference for the exploration of the coal seam permeability increasing mechanism of hydraulic fracturing.

1. Introduction
Hydraulic fracturing technology is using fracturing pump set to inject high pressure dynamic water higher than the initiation pressure into the coal seam, so as to produce fractures in the coal seam, and continuously inject high pressure dynamic water to develop and expand the fractures in the coal seam, so as to achieve the purpose of increasing the permeability of coal seam and improving the effect of gas extraction [1-2]. Since the introduction of hydraulic fracturing technology in China, most of the research results on the stress-strain evolution law in hydraulic fracturing process are obtained through the establishment of theoretical mechanical model, and few field tests. There are many methods of stress-strain monitoring of coal and rock mass in underground coal mine [3-4]. Among them, hollow inclusion stress gauge is widely used in underground coal mine [5-6]. Six stress components ($\sigma_x$, $\sigma_y$, $\sigma_z$, $\tau_{xy}$, $\tau_{yz}$, $\tau_{zx}$) of the three-dimensional stress change tensor can be determined by a single drilling borehole. At present, some domestic scholars have carried out stress and strain monitoring tests for hydraulic fracturing of coal seam roof. Huang Fei et al. [7] used hollow inclusion stress gauge to monitor the roof stress and strain evolution law during hydraulic fracturing in Tonghua Coal Mine in Songzao mining area, and reached the conclusion that hydraulic fracturing could change the stress state of coal seam roof. Kang Hongpu et al. [8] used a hollow inclusion stress meter to monitor the change of coal seam stress...
near the borehole before and after hydraulic fracturing in Wangtaipu Coal Mine of Jincheng, and found out the stress evolution law and influencing factors in the process of hydraulic fracturing. They believed that the roof of coal seam could be effectively weakens by directional hydraulic fracturing. The above field tests are all for monitoring the hydraulic fracturing of coal seam roof, but there are few reports on the field tests of stress and strain monitoring of coal seam hydraulic fracturing. Therefore, this paper carried out the field practice of coal seam hydraulic fracturing stress and strain monitoring to explore the stress evolution law of hydraulic fracturing in this coal seam.

2. On-site implementation of stress and strain monitoring

The test site is selected in a coal mine gas extraction lane, hydraulic fracturing K2 coal seam, the inclination is 30°, the average thickness is 1.5m. The roof of coal seam is dark gray mudstone (0.25m) and argillaceous limestone (4.57m). The floor of the coal seam is sandy mudstone (3.2m). The buried depth of the test area is between 800 and 810m. In this test, one perforation hydraulic fracturing borehole and two stress and strain monitoring boreholes were designed. The design parameters are shown in Table 1, and the layout of drilling boreholes is shown in Fig. 1.

| Borehole type                  | Aperture/mm | Dip angle/° | Angle with cross-entry/° | Length/m | End borehole location          |
|-------------------------------|-------------|-------------|--------------------------|----------|-------------------------------|
| 1# monitor borehole           | 130mm       | 10          | 45                       | 38m      | Siliceous limestone           |
| 2# monitor borehole           | 130mm       | 33          | 0                        | 17m      | Siliceous limestone           |
| Hydraulic fracturing borehole | 108mm       | 22          | 0                        | 69m      | K2 coal seam                  |

KX-81 hollow inclusions strain gauge (precision 0.1μs) and KJ327-F mine pressure monitoring system sub-station (precision measurement value ±0.1% word) were used to monitor the stress and strain in the process of hydraulic fracturing. The stress-strain monitoring equipment is shown in Fig. 2.
3. Analysis of stress-strain monitoring results

3.1. Analysis of strain monitoring results
Strain is closely related to the pressure borne by the borehole wall and the formation and expansion of cracks, which is the manifestation of the formation and expansion of cracks in the borehole wall under the action of water pressure. Field strain data collection is set to take 20 minutes for each collection, and the collection frequency is once per minute. Before fracturing, the strain gauge is connected, and the fracturing pump is activated and the fracturing is monitored in real time. After fracturing, data collection will be carried out every day, and stress-strain data will be analyzed every day. Monitoring will be stopped when it is found that data tend to be stable. Due to the large amount of stress-strain data collected in the field, it was found through analysis that the stress-strain variation rules of the two stress gauges were similar. In this paper, only the representative strain monitoring data of the monitoring 1# borehole was listed for analysis. The monitoring data were plotted into the strain curve of the whole hydraulic fracturing process, as shown in Fig. 3.

As can be seen from Fig. 3, two hours after hydraulic fracturing, fracturing water has affected the stress monitoring point, and has reached the maximum, up to 32m. At the later stage of fracturing, the strain tends to remain stable without large changes. It can be inferred from the coal seam geological histogram that there is no pressure through the coal seam floor during the whole fracturing process. After fracturing, the strain gradually recovered. At 6 days after fracturing, the strain returned to a stable
state without any change, but it was still slightly larger than that before fracturing, indicating that hydraulic fracturing had changed the stress state of coal and rock mass.

3.2. Analysis of stress monitoring results
Stress monitoring can indirectly describe the stress change of coal seam roof by monitoring the strain of surrounding rock. In general, the increment of stress can be more convenient to show the change rule of stress, and the increment of principal stress can be calculated by inputting the monitoring data into the program. In this paper, the principal stress increment is used to represent the change of principal stress. The maximum, intermediate and minimum principal stress increments are $\Delta \sigma_1$, $\Delta \sigma_2$ and $\Delta \sigma_3$ respectively when the stress meter is just embedded and the reading is stable.

(1) Principal stress increment analysis of 1# borehole

As shown in Fig. 4, on the day of fracturing, high-pressure water cracks in the relatively soft coal seam first, and the stress (principal stress increment $\Delta \sigma_3$) changes most obviously in the vertical direction of fracturing in the No.1 stress monitoring borehole. Day 3 after fracturing: principal stress increment began to decrease, $\Delta \sigma_3$ drops to about 8 MPa, coal and rock and borehole wall in some areas appear the phenomenon of elastic compression, the stress monitoring borehole storage energy, when after fracturing has stopped, in the coal and rock stress decreases, the elastic deformation of the borehole wall gradually restored, the deformation has a tendency to gradually return to the initial state, show is the principal stress increment decreases. Day 4 after fracturing, the increment of the principal stress increased, and the azimuth angle and inclination angle changed greatly. Because the fracturing borehole kept the pressure, the high-pressure water continued to act on the coal and rock mass, infiltrated into the coal and rock mass and changed the mechanical properties of the coal and rock mass, thus affecting the increment of the principal stress and the change of the direction. Day 5 after fracturing, the fracturing borehole was relieved, and the increment of principal stress continued to decrease, and the decreasing rate increased, the fracturing fluid loss rate in the coal and rock masses accelerated, and the pressure gradually returned to the original state. Day 6 after fracturing: the increment of principal stress continues to decrease, the rate slows down, and the stress level in coal and rock gradually tends to be stable, but it is still larger than the state before fracturing. Hydraulic fracturing affects the 1# monitoring borehole, which reaches 32m, and changes the stress state of coal seam roof. During the fracturing process, the pressure of the high-pressure pump was about 22MPa, but the principal stress increment of the stress monitoring borehole was about 8.5MPa at most. Because in the fracturing process, there is inevitably pressure loss as the high-pressure water flows to the stress monitoring borehole.
As shown in Fig. 5, the azimuth angle and inclination angle of the stress on coal and rock mass changed with time. On the day of fracturing, hydraulic fracturing affected the 1# stress monitoring borehole, leading to a sharp change in the stress state of surrounding rock. In general, in the monitoring period, hydraulic fracturing has a great influence on the azimuth of the principal stress increment $\Delta \sigma_2$, and has little influence on the azimuth and dip angles of other principal stresses, and each stress state gradually returns to the initial state.

(2) Principal stress increment analysis of 2# borehole

The change curve of principal stress increment in monitoring borehole 2# is shown in Fig. 6. On the day of fracturing, the principal stress increment in monitoring borehole 2# increases in all three directions, but mainly in the vertical direction, while the stress increment in other directions is small. Because the 2# monitoring borehole is far from the pressure cracking borehole (47m away) and is subject to the resistance of coal and rock mass, when the fracturing fluid is transferred from the pressure cracking borehole to the 2# monitoring borehole, the pressure loss is large, the principal stress increase of the 2# monitoring borehole is small, and the fracturing fluid is spread to the 2# monitoring borehole, and the influence range is not less than 47m. After hydraulic fracturing, the decrease rate of stress increment in monitoring borehole 2# is faster than that in monitoring borehole 1#, because the location of monitoring borehole 2# is far away, the stress recovery rate is faster, and the stress increment basically returns to the original state on the 6th day after fracturing.
The change curve of azimuth and dip angle of the principal stress of coal and rock mass around the 2# monitoring borehole as shown in figure 7, on the fracturing day, 2# monitoring borehole three-way azimuth angle and dip angle of principal stress influenced by fracturing has some changes, but quickly recovered after fracturing, gradually stabilized, because 2# borehole in place far away from the pressure, compared with 1# borehole, change smaller, faster recovery.

4. Conclusion

(1) The strain of the whole process of hydraulic fracturing was monitored, and the analysis showed that: 2 hours after the fracturing began, the high-pressure power water spread to the monitoring borehole, the influence range was no less than 47m, and the influence reached the maximum, and the strain tended to be stable in the later stage of fracturing. After fracturing, the strain gradually recovered. At 6 days after fracturing, the strain returned to a stable state without any change, but it was still larger than that before fracturing, indicating that hydraulic fracturing had changed the strain state of coal and rock mass.

(2) By analyzing the increment of principal stress in the whole process of hydraulic fracturing, it can be seen that hydraulic fracturing changes the stress state of coal and rock mass, and the fracturing range reaches the monitoring borehole area, which is no less than 47m. The increment of principal stress increases, but the increment of vertical stress changes the most. After pressure relief, the stress increment decreases gradually and tends to return to the original stable state, but it is still larger than the state without hydraulic fracturing. Hydraulic fracturing has little effect on the azimuth and dip angle of coal and rock mass.

References

[1] Wang Zhilei. Research on Hydraulic Fracturing Technology of Low Permeability Coal Seam [D]. Beijing: China University of Mining and Technology (Beijing), 2015.
[2] Deng Guangzhe, Wang Shibin, Huang Bingxiang. Study on fracture propagation behavior of coal rock under water pressure [J]. Chinese Journal of Rock Mechanics and Engineering, 2004, 23(20): 3489-3493.
[3] Yan Zhenxiong, Guo Qifeng, Wang Peitao. Calculation Method and Application of In-situ Stress Component in Hollow Inclusion Strain Gauge [J]. Rock and Soil Mechanics, 2018(2): 715-721.
[4] Liu Ning, Zhang Chunsheng, Chen Xiangrong, et al. Study on stress evolution process monitoring and characteristics of surrounding rock during excavation of deep tunnel [J]. Chinese Journal of Rock Mechanics and Engineering, 2011, 30 (9): 1729-1737.
[5] NI Xinghua. Research and application of in-situ stress [M]. Beijing: Coal Industry Press, 2007: 52-129.
[6] Liu Chaoru. Research on In-situ Stress Distribution Characteristics of Deep Coal Mine and Its
Influence on Stress Field of Roadway Surrounding Rock [D]. Beijing: China Coal Research Institute, 2012.

[7] Huang Fei, Li Shuqing, Zuo Weiqlin. Mining Engineering Research, 2018, 33(3): 23-27.
[8] Kang Hongpu, Feng Yanjun. Journal of China Coal Society, 2012, 37(12): 1953-1959.