Characteristics of hydraulic fracture surface based on 3D scanning technology

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The surface characteristics of fractured specimens are important in hydraulic fracturing laboratory experiments. In this paper, we present a three-dimensional (3D) scanning device assembled to study these surface characteristics. Cube-shaped rock specimens were produced in the laboratory and subjected to triaxial loading until the specimen split in two in a hydraulic fracturing experiment. Each fractured specimen was placed on a rotating platform and scanned to produce 3D superficial coordinates of the surface of the fractured specimen. The scanned data were processed to produce high-precision digital images of the fractured model, a surface contour map and accurate values of the superficial area and specimen volume. The images produced by processing the 3D scanner data provided detailed information on the morphology of the fractured surface and mechanism of fracture propagation. High-precision 3D mapping of the fractured surfaces is essential for quantitative analysis of fractured specimens. The 3D scanning technology presented here is an important tool for the study of fracture characteristics in hydraulic fracturing experiments.

1. Introduction

Hydraulic fracturing is an effective method for coalbed methane (CBM) drainage that is widely used in coal mines globally [1]. Hydraulic fracturing is influenced by multiple factors, including in situ stress in a coal seam, natural fractures, mechanical parameters of coal rock and flow rate [2–5]. The main fracture propagates parallel to the direction of maximum horizontal stress. There are different types of natural fractures in coal seams, these cause anisotropy and discontinuity in the coal rock and greatly affect the deformation and mechanical strength...
of coal rock, permeability of CBM reservoirs and fracture network [6]. The mechanical parameters of coal rock are the basis for studying the mechanism of hydraulic fracturing in CBM reservoirs.

A hydraulic fracturing experiment is an effective method to study the efficiency and mechanism of hydraulic fracturing [7]. Such experiments can monitor hydraulic fracturing visually and over time. Many studies have focused on fracture morphology and mechanism of propagation [8]. Experimental devices for monitoring hydraulic fracturing include computed tomography (CT) scanning, tracer agents, digital photography, acoustic emission and microscopic observation [9–12]. Zou et al. [9] found that CT scanning was an effective method for revealing fracture geometry in natural bedding developed shale; CT scan images could display directly the fracture network in fractured shale. Ishida [10] conducted hydraulic fracturing experiments by granitic rock specimens with different grain sizes and found that shear fracturing or tensile fracturing played different roles in fracture propagation processes through acoustic emission. Moreover, acoustic emission was monitored by a borehole sonde in field fracturing to measure rock stress. Stanchits et al. [11] carried out hydraulic fracturing experiments by means of sandstone under conditions of different injection rates and fluid viscosity; monitoring of acoustic emission could indicate the development of fractures. Chen et al. [12] conducted hydraulic fracturing experiments to study the effect of fluid viscosity on fracture propagation and fractures were microscopically observed via a fluorescent method.

Besides, when fracturing fluid is flowing in a specimen, the structure and roughness of the fractured specimen directly affect the fracture morphology and propagation [13,14]. However, the processes related to fracture morphology and mechanism of fracture propagation are not well understood, and relevant research on the roughness and structure of fractured specimens is scarce. There are difficulties in accurately monitoring the superficial structure and roughness of fractured specimens using existing monitoring equipment. Moreover, studies on the characteristics of fractured specimens lack qualitative descriptions and are short of quantitative analysis. Therefore, it is important to develop an effective device that can extract the characteristics of fractured rock specimens. In this article, a three-dimensional (3D) scanning device is used to scan a fractured rock specimen, based on the scanned data the following characteristics of the fractured specimen are extracted: 3D coordinates, superficial area, volume, shaded relief image, 3D scanned image and contour map. Compared with digital photos, the characteristics extracted from the fractured specimen using the 3D scanner provide clearer and more detailed observations of the structure, roughness and variations of the fractured surface. The technique presented in this paper can be used to obtain quantitative information of specimens in hydraulic fracturing experiments.

2. Description of hydraulic fracturing experimental device

2.1. Device for three-dimensional scanning of coal rock specimens

The main components of the 3D scanning device are two OKIO-B non-contact 3D scanners, a rotating platform (figure 1) and 3D scanning software. The device performs fast non-contact scanning and provides 3D coordinates of the scanned object. A 3D model of the surface of the fractured specimen is produced and displayed automatically based on the high-precision extracted 3D coordinates.

Compared with CT scanning, the device has the advantages of low cost and short experiment time. The 3D scanning image of the target can be observed in real time during the scanning process. The OKIO-B non-contact 3D scanner is easy to operate and has a high-precision charge-coupled device sensor, which has been widely applied to industrial and geotechnical engineering. The 3D scanning precision ranges from 0.01 to 0.02 mm and the 3D scanning average distance ranges from 0.07 to 0.15 mm.

After hydraulic fracturing, the fractured specimen is placed on a rotating platform for non-contact 3D scanning to obtain the structure, roughness and other characteristics of the fractured specimen. As the specimen is made of cement, gypsum and pulverized coal, there will be black spots upon the surface of the fractured specimen. Black spots on the surface of the fractured specimen will result in blanks. Because the black spots cannot be scanned to form a 3D model, dye penetrant inspection materials are used on the specimen to fill these blanks.

2.2. Hydraulic fracturing experimental system

The hydraulic fracturing system is composed of a true triaxial hydraulic fracturing device, fracturing pump system, data collection system and other components, as shown in figure 2.
3. Example tests

3.1. Specimens

The identical cube specimens (figure 3) were of dimensions $200 \times 200 \times 200$ mm and made of cement, gypsum and pulverized coal. The coal rock was collected from coal seam no. 4 of the Xintian Coal Mine in Guizhou province, China. Its uniaxial compressive strength is 8.53 MPa, tensile strength is 0.63 MPa, elastic modulus is 0.82 GPa, Poisson’s ratio is 0.28 and firmness coefficient (Protodayakov’s coefficient)
3.2. Characteristics of the fractured surface

A cube specimen was placed under a horizontal stress difference of 1.50 MPa, the fracturing fluid rate is 3.2 ml s$^{-1}$ and the characteristics of the fractured specimen were analysed by the 3D scanning device, as shown in figure 4.

The flow path of fracturing fluid can be inferred from the red zone on the fractured specimen, as shown in figure 4. We can deduce the fracture morphology and propagation from the digital photo. The black spots on the fractured surface cannot be accurately scanned; therefore, they are filled with dye penetrant inspection material before scanning. To obtain a full set of 3D data points of the fractured surface, the specimen is placed under the OKIO-B non-contact high-precision 3D scanner on a continuously rotating platform. The scanned data are processed automatically to produce the 3D model.

Figure 4 shows that the fracture propagates perpendicular to the direction of minimum horizontal stress. The characteristics of the fractured surface, including the shaded relief model, 3D scanning image, contour map, superficial area, volume and 3D coordinates, can be derived by the 3D scanning device.

Compared with the digital photograph of the fractured specimen (figure 5a), the 3D shaded relief image (figure 5b) produced by the 3D scanner presents a much clearer view of the variation and roughness of fractured surface. The 3D coloured scanning image (figure 5c) illustrates the fine structural details of the fractured surface. The contour map of the fractured surface is shown in figure 5d,

is 0.80. To make the mechanical parameters of coal rock close to those of similar materials an experimental programme is designed to study the mechanical parameters of similar materials. After a series of ratio tests, a ratio (the proportion of cement, gypsum, pulverized coal was 2 : 1 : 1) was chosen to form the cube specimens. The material was tested to obtain its mechanical parameters, which were close to those of coal rock. The test yielded a compressive strength of 5.38 MPa, tensile strength of 0.60 MPa, elastic modulus of 0.78 GPa, Poisson’s ratio of 0.25 and firmness coefficient of 0.82.

Figure 3. Cube specimens made of similar materials.

Figure 4. Fractured specimen showing ‘red zone’ indicting fluid propagation path.
Figure 5. 3D imaging and map produced by the 3D scanner: (a) digital image of the fractured specimen; (b) shaded relief model of the fractured specimen; (c) 3D scanning image of the fractured specimen; and (d) contour map of the fractured specimen.
areas where the contour lines are close together represent a more complex fracture pattern, where the dynamic effect of the fracturing fluid is stronger and the flow rate is higher. Based on the 3D coordinate dataset, the superficial area of fractured surface and volume of fractured specimen are 41820.67 mm² and 3317200.78 mm³, respectively.

4. Conclusion

A 3D scanning device was used to scan the surface of fractured rock specimens and extract the surface characteristics. The specimens were fractured in a hydraulic fracturing experiment. The scanned data were processed to produce a shaded relief model of the fractured specimen, a 3D scanning image and a contour map of the fractured surface, generating a clear and detailed representation of the fracture morphology and propagation. A new method is proposed to quantitatively study hydraulic fracturing. Using the 3D coordinates extracted from the scanner, the superficial area of the fractured surface and volume of the fractured specimen can be derived for quantitative analysis. The 3D scanning device for coal rock specimens is an efficient diagnostic tool for hydraulic fracture experiments.

Data accessibility. The data can be accessed in the electronic supplementary material.

Authors’ contributions. F.Z. and G.M. conceived the experiments. F.Z., X.L. and Y.L. performed the experiments. F.Z., Y.T. and R.L. analysed the experimental results and prepared the manuscript. All authors reviewed the manuscript and gave final approval for publication.

Competing interests. We declare we have no competing interests.

Funding. The authors gratefully acknowledge the financial support from Major Work on Innovation Methods of the Ministry of Science and Technology of China in 2016 (grant no. 2016IM010400) and the National Natural Foundation of China in 2014 (grant no. 71472171).

Acknowledgements. We thank Jiang Xu, Dan Feng for comments on the manuscript; Hu Tan for his statistical guidance throughout the project. We are grateful to Shoujian Peng, who provided fundamental contribution to the experimental devices.

References

1. Majdi A, Hassani FP, Nasiri MY. 2012 Prediction of the height of destressed zone above the mined panel roof in longwall coal mining. Int. J. Coal Geol. 98, 62–72. (doi:10.1016/j.coal.2012.04.005)
2. Karacan CO, Okandan E. 2000 Fracture/cleat analysis of coals from Zonguldak Basin (northwestern Turkey) relative to the potential of coalbed methane production. Int. J. Coal Geol. 44, 109–125. (doi:10.1016/S0166-5162(00)00004-5)
3. Jiang T, Zhang J, Wu H. 2017 Impact analysis of multiple parameters on fracture formation during volume fracturing in coalbed methane reservoirs. Curr. Sci. 112, 332–347. (doi:10.18520/cs/v112/02/0332/347)
4. Huang S, Liu D, Yao Y, Gan Q, Cai Y, Xua L. 2017 Natural fractures initiation and fracture type prediction in coal reservoir under different in-situ stresses during hydraulic fracturing. J. Nat. Gas Sci. Eng. 43, 69–80. (doi:10.1016/j.jngse.2017.03.022)
5. Dehghani AN, Gochitsuki K, Ahangari K, Jin Y. 2016 Mechanism of fracture initiation and propagation using a tri-axial hydraulic fracturing test system in naturally fractured reservoirs. Eur. J. Environ. Civil Eng. 20, 560–565. (doi:10.1080/19648189.2015.1056384)
6. Li Q, Lin B, Zhai C. 2014 The effect of pulse frequency on the fracture extension during hydraulic fracturing. J. Nat. Gas Sci. Eng. 21, 296–303. (doi:10.1016/j.jngse.2014.08.019)
7. Jiang T, Zhang J, Wu H. 2016 Experimental and numerical study on hydraulic fracture propagation in coalbed methane reservoir. J. Nat. Gas Sci. Eng. 35, 455–467. (doi:10.1016/j.jngse.2016.08.077)
8. Guo T, Zhang S, Qu Z, Zhou T, Xiao Y, Gao J. 2014 Experimental study of hydraulic fracturing for shale by stimulated reservoir volume. Fuel 128, 373–380. (doi:10.1016/j.fuel.2014.03.029)
9. Zou Y, Zhang S, Zhou T, Zhou X, Guo T. 2016 Experimental investigation into hydraulic fracture network propagation in gas shales using CT scanning technology. Rock Mech. Rock Eng. 49, 33–45. (doi:10.1007/s00603-015-0720-3)
10. Ishida T. 2001 Acoustic emission monitoring of hydraulic fracturing in laboratory and field. Constr. Build. Mater. 15, 283–295. (doi:10.1016/S0950-0618(00)00177-5)
11. Stanchits S, Burghardt J, Sarabi A. 2015 Hydraulic fracturing of heterogeneous rock monitored by acoustic emission. Rock Mech. Rock Eng. 48, 2539–2547. (doi:10.1007/s00603-015-0848-1)
12. Chen Y, Nagaya Y, Ishida T. 2015 Observations of fractures induced by hydraulic fracturing in anisotropic granite. Rock Mech. Rock Eng. 48, 1455–1461. (doi:10.1007/s00603-015-0727-9)
13. Kulatilake PHSW, Um J, Panda BB, Highem N. 1998 Development of a new peak shear-strength criterion for anisotropic rock joints. Int. J. Rock Mech. Min. Sci. 35, 418–420. (doi:10.1016/S0148-9062(98)00056-4)
14. Andrade PS, Saravia AA. 2008 Estimating the joint roughness coefficient of discontinuities found in metamorphic rocks. Bull. Eng. Geol. Environ. 67, 425–434. (doi:10.1007/s10094-008-0151-4)