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The fractal characteristics and energy mechanism of crack propagation in tight reservoir sandstone subjected to triaxial stresses

Yongming Yang [a], Yang Ju [b, c, *], Fengxia Li [d], Feng Gao [c], Huafei Sun [a]

[a] School of Mechanical & Civil Engineering, China University of Mining and Technology, Beijing 100083, China
[b] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology at Beijing, Beijing 100083, China
[c] State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining & Technology, Xuzhou 221116, China
[d] Research Institute of Petroleum Exploration and Development, SINOPEC, Beijing 100083, China

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A B S T R A C T

A series of triaxial compression and microfocus CT scanning tests of tight reservoir sandstone were implemented to investigate its three-dimensional (3D) crack propagation behavior. The 3D geometric morphology and distribution characteristics of the cracks under various triaxial stresses were studied. Three-dimensional reconstruction models of the crack morphology were established and the influences of confining pressures on crack propagation were probed. The fractal theory was used to describe the rough morphology of the crack surfaces. The energy mechanism that governs crack growth was analyzed using the energy theories and principles. Energy dissipation and energy release laws were proposed to characterize crack growth under various triaxial stresses. The results indicate that triaxial stress has a great effect on the quantity, geometry and spatial distribution features of cracks. In the fractured sandstone sample, a lower confining pressure induces numerous macroscopic cracks accompanied by microcracks; they interconnect to form an intricate crack network. In contrast, a higher confining pressure results in a small number of macroscopic cracks whose surfaces present a simple geometry, similar to a plane surface. The fractal dimension of crack surfaces decreases linearly with the increase in confining pressure. Meanwhile, the releasable elastic strain energy rises and the dissipated energy density decreases linearly when increasing the confining pressure.

1. Introduction

With rapid economic development, the energy supply is experiencing a serious shortage throughout the world. As a result, people are paying increasing attention to unconventional oil and gas resources, such as coalbed methane, tight reservoir gas, shale oil, and shale gas. Currently, the main exploitation method for unconventional oil and gas resources is to break in-situ reservoir rocks to form crack channels using techniques such as hydraulic fracturing. The fractured cracks inside the rocks are the main pathways of seepage, migration, and drainage for oil and gas. However, the mechanical properties of reservoir rock feature high nonlinearity and heterogeneity. Moreover, the geological environment and stress conditions in deep rock formations are extremely complex. Geoscientists do not have adequate knowledge of crack growth and the formation mechanism of rock under in-situ stress and hydraulic pressure. This lack of knowledge has resulted in many intractable issues that remain to be resolved regarding the large-scale application of effective exploitation technology (Holditch, 2013, Li et al., 2012). To overcome the above challenges, the key initial scientific problem is to understand the characteristics of the crack propagation mechanism in tight rock under triaxial stresses. These characteristics include the crack geometric morphology, the spatial distribution features and the energy mechanism during crack initiation and growth. It is important to understand the crack propagation mechanism of tight reservoir rocks under triaxial stresses to safely and efficiently exploit unconventional oil and gas resources.

In the 1950s, many theoretical models for crack growth in rock were developed and established (Green and Sneddon, 1950; Nordren, 1972 and Perkins and Kern, 1961). Subsequently, researchers performed many experiments to study the crack

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* Corresponding author. State Key Laboratory of Coal Resources & Safe Mining, State Key Laboratory for Geomechanics & Deep Underground Engineering, China University of Mining & Technology, D11 Xueyuan Road, Beijing, 100083, China. Tel./fax : +86 10 62331253.
E-mail addresses: juy@cumtb.edu.cn, yju@icloud.com (Y. Ju).

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propagation laws in rock (Al-Shayea, 2005; Eberhardt et al., 1998; Parka and Bobetb, 2010; Tang and Li, 2014; Warpinski et al., 1982). In recent decades, with the development of numerical simulation methods, more and more scientists have probed crack propagation in rock on the basis of numerical methods (Camonesa et al., 2013; Ju et al., 2013; Sato et al., 2001; Swan, 1975 and Yang et al., 2015). To characterize the geometric morphology of cracks, fractal theories were applied to describe the crack system (Laubach et al., 2000; EI Ouahed et al., 2005 and Xie and Chen, 1989). The aforementioned research works are helpful in understanding the crack propagation mechanism of rock. However, reservoir rock is a type of heterogeneous material. Crack propagation behavior is an extremely complex process, especially under triaxial stresses. It is currently not possible to accurately characterize the irregular geometric morphology of cracks and relate it to the external geostress conditions. There is a lack of full and accurate knowledge of the mechanism of influence of triaxial stresses on crack propagation, including the quantity, geometric morphology, spatial distribution of cracks and energy features. More work exploring the crack propagation mechanism is needed to meet the needs of engineering applications.

To study these influences and mechanisms, in this paper, we performed a series of triaxial compression and CT scanning tests of tight reservoir sandstone subjected to various confining pressures by means of triaxial testing and CT imaging techniques. The 3D morphology and distribution of cracks in fractured tight rock were imaged under various confining pressures. Based on image processing techniques and statistical principles, reconstructed models of the 3D crack geometric morphology were established under various confining pressures. The geometric distribution characteristics and fractal features of the crack surfaces were analyzed. The influences of the confining pressures on crack propagation were discussed. Lastly, the energy mechanism that governs crack growth in tight rock was elucidated. This study helps to understand the mechanism that governs crack propagation in tight reservoir sandstone subjected to complex triaxial stresses.

2. Triaxial compression and CT scanning tests of tight sandstone

2.1. *Materials and specimen preparation*

Tight sandstone was derived from the rock stratum at a depth of 900 m in a certain mining area in northern China. To eliminate the influence of divergence in the mechanical properties and lithology of sandstone on the experimental results, the tight sandstone samples were all selected from a small region in the rock stratum at a depth of 900 m. This selection ensures that all of the test samples feature the same or similar lithology and mechanical properties. Employing the uniaxial compression tests and the acoustic emission Kaiser Effect test, we obtained the mechanical properties of the sandstone samples. The samples had an elastic modulus E of 70.18 GPa, Poisson's ratio ν of 0.157 and maximum horizontal crustal stress of 29.6 MPa. The sandstone samples were processed into cylinders with a diameter of 50 mm and a height of 100 mm. Both planes of the cylindrical samples were polished to ensure that the planes were perpendicular to the loading axis. Fig. 1 demonstrates a prepared specimen of tight sandstone for triaxial tests.

Fig. 1. Photograph of a tight sandstone specimen.

2.2. *Triaxial compression tests*

A TAW-2000 rock electro-hydraulic servo triaxial testing system was employed for the triaxial compression tests of tight sandstone. To analyze the influence of triaxial stresses on the crack growth characteristics of tight sandstone, we designed 6 groups with different confining pressures according to the actual horizontal crustal stresses: 5 MPa, 10 MPa, 15 MPa, 20 MPa, 25 MPa and 30 MPa. The corresponding sample numbers were $1^{\#}$, $2^{\#}$, $3^{\#}$, $4^{\#}$, $5^{\#}$ and $6^{\#}$, respectively. During loading, the confining pressure was constant and the axial pressure gradually increased until the sandstone samples were broken. The loading mode was kept static by controlling the displacement, and the loading ratio was 0.2 mm/min Fig. 2 plots the triaxial stress-strain curves under various confining pressures. Fig. 3 presents photographs of the fractured sandstone samples. Table 1 lists the triaxial compressive strengths.

2.3. *CT scanning tests and processing of the crack images*

After the triaxial compression tests, we carried out CT scanning tests of tight sandstone. The crack population was imaged and characterized at the moment when the maximum fracturing load was reached. The fractured tight sandstone specimen was taken out of the triaxial loading chamber after it experienced the maximum longitudinal load and was placed on the CT machine to perform tomography. The CT test system, with a high precision 16-bit sensor and a spatial resolution up to 4 μm, is shown in Fig. 4. In the CT tests, 100 transverse sections of each sample were consecutively

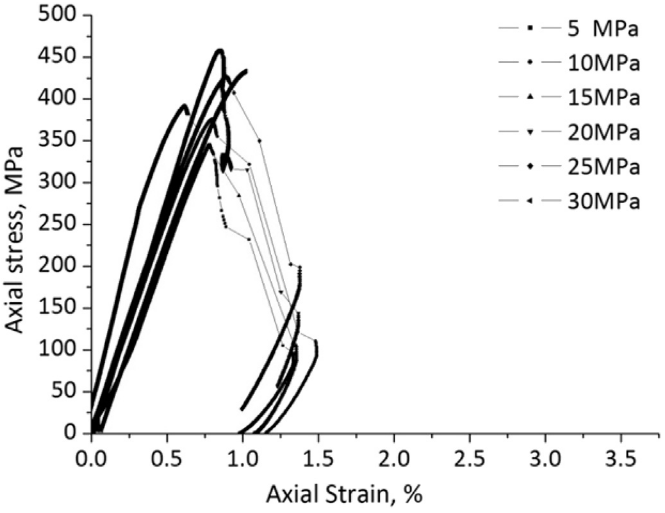

Fig. 2. Triaxial stress-strain curves under various confining pressures.