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A comprehensive analysis of fracture initiation and propagation in sandstones based on micro-level observation and digital imaging correlation

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ABSTRACT

Along with the development of the oil & gas industry, the word "fracture" is now a quite familiar subject to well stability and integrity over the drilling process. However, the fracturing mechanisms are still less convincing though a large amount of literature have addressed the subject matter. In this paper, a new comprehensive experimental method is proposed herein to analyze the fracturing mechanisms through a micro-level observation to a macro explanation.

To assess the tensile resistance of rock, Brazilian Test was applied to disc-shaped specimens of isotropic sandstones. Meanwhile, a high-speed photography system was keeping snapping images for the digital imaging correlation (DIC) to get a dynamic fracturing process. After the specimen failed and was split, the cuttings were analyzed using scanning electron microscope (SEM) and electron-dispersive system (EDS) for a micro-level observation.

Two kinds of fracturing mechanisms were identified as: (1) grain fracturing, and (2) pore-fillings fracturing. Three basic fracture modes (Mode I/II/III) can also be distinguished through (1) the grain size, and (2) the grain shape and uniformity using a new parameter named angularity factor. The DIC technique proved to be a powerful analysis tool, especially showing the sequence of fracture initiation, propagation and termination. Though the cracks can be initiated from the center or near the loading points, the main direction of fracturing propagation was still along the diametric loading plane. In addition, a displacement along the thickness was also identified through a 3-D investigation, which should be of interest due to the scarcity of relevant literature in 3-D effect on standard 2-D Brazilian Test.

1. Introduction

To keep the integrity and stability of the wellbore wall, many researchers have investigated the fracturing mechanisms of rocks over the drilling process. Most of the current theoretical mechanisms are based on the principles of brittle fracture mechanics proposed by Griffth A.A., also known as Griffith's Brittle Fracture Theory (Griffith, 1921). According to the theory, the failure was caused by the tensile stress induced at the tips of existing cracks or joints that are oriented at a critical angle to the applied principle stresses. Then, Irwin (1957) made an important modification to the theory and proposed a stress intensity factor (SIF), normally referred to fracture toughness. It is a measurement of the ability of a material to resist an unstable fracture propagation. Based on a modified Griffith's Brittle Fracture Theory, Colback (1966) developed an analytical fracture model for a disc-shaped isotropic specimen, using Frocht's (Frocht, 1947) principal stress distribution equations of an isotropic rock, and verified that the fracture could occur at the disc center and propagate along the loaded diametrical plane.

To estimate the rock strength, there are mainly two kinds of measurement methods: (1) The static testing methods include uniaxial compression, tri-axial compression, Brazilian Test (diametrical compression), bending test, torsion and hollow cylinder test. (2) The dynamic methods contain resonant bar method and ultrasonic pulse method (Homand et al., 1993; Amadei, 1996). Among these methods, Brazilian Test is preferred in laboratory testing due to its simplicity and efficiency, which can also remove extraneous bending effects and stress concentrations at irregular peaks (Colback, 1966; Homand et al., 1993; Alabi et al., 2017). In a Brazilian test, the length/diameter ratio should be 0.2 to 0.7 for disc-shaped specimens (Mokhtari et al., 2017). The specimen is mounted and loaded diametrically by two opposing normal strips at the top and the bottom. To minimize the compression effect near loading points, the load should be applied evenly by strips which cover a

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loading angle about 19.5° to the core center (Elghazel et al., 2015; Mahanta et al., 2017; Rocco et al., 1999). However, the tensile strength measurement is only valid when the crack is initiated at the planar center of an isotropic brittle material (Colback, 1966; Balbo, 2013; Mokhtari et al., 2017; Chen et al., 1998). For anisotropic rock material, the measured splitting tensile stress is dependent on the measurement angle between the loading direction and the lamination (Alabi et al., 2017). Nevertheless, there are many other parameters, such as the specimen size, the particle size distribution, and the strain rate (Sabri et al., 2016; Mahanta et al., 2017; Rocco et al., 1999).

Rock fracture mechanics are mostly concerned with the initiation and propagation of a crack and rock deformation. Apart from the small micro-cracks and micro-defects inside the rock matrix, the cracks can also propagate through pre-existing large-scale fractures (Wu et al., 2017). Normally, rock failure patterns can be classified into three basic modes as shown in Fig. 1. For all three basic fracture modes, Mode I indicates a tensile failure mode and is usually considered as the dominant failure mode under Brazilian testing condition. However, it always turned out as a complex interaction with the shear fractures Mode II and torsion fractures Mode III (Ayatollahi and Aliha, 2008; Aliha and Ayatollahi, 2011; Backers, 2005). Standardized by the International Society for Rock Mechanics (ISRM), several methods are widely used for the fracture toughness measurement (Fowell, 1995; Ulusay, 2014). In the last two decades, there have been many testing procedures and analysis on the measurements of fracture toughness of Mode I fracture and Mode II fracture (Alabi et al., 2017; Wu et al., 2017; Wei et al., 2016; Sabri et al., 2016; Elghazel et al., 2015; Mahanta et al., 2017; Hua et al., 2017). Yet, few studies dealt with the fracture toughness of Mode III (Aliha et al., 2015).

Though many studies have made significant contributions toward the explanation of rock fracturing, the initiation of fracture and propagation mechanism of the same is still not fully understood. Readers cannot be convinced by most of the proposed theories, analytical solutions, or numerical simulations, which usually require many assumptions to simplify the fracturing process and analyze the rock deformation on an ideal basis. Since a fracture is created all of a sudden, traditional experimental results usually only show the final crack patterns but exhibit no evidence of the initiation and propagation of a fracture. Thanks to the rapid development of the high-resolution cameras and computational technologies in the last 30 years, a digital imaging correlation (DIC) technique has been widely utilized to measure the displacement contours (Sutton et al., 1983; Schreier et al., 2000). In mechanics-related areas, it has been applied in measuring the strength of concrete, refractories and ceramics (Belrhiti et al., 2016; Belrhiti and Pop, 2013; Vargas et al., 2016; Ganganagoudar et al., 2016; Robert et al., 2007; Khlifia et al., 2017). Besides, scanning electron microscope (SEM) is now widely used to study rock microstructures. It can reveal the micro-level topography of the grain surface, pore geometry and pore fillings. Normally attached to SEM, an energy-dispersive system (EDS) analyzer is used for the elemental distribution and mineral identifications using X-ray spectroscopy. Thus, we can identify different mineral phases present in the rock and figure out how the grain fails in the path of fracture (Sabri et al., 2016; Elghazel et al., 2015; Mahanta et al., 2017).

To further study the fracture mechanisms over the drilling process, this paper proposes a new comprehensive fracturing analysis, using a micro-level observation and a digital imaging correlation. The analysis procedure and mechanical testing results are presented in section 2 and 3, respectively. Then, we combine the digital imaging correlation of dynamic photography with the fracture initiation and propagation in Section 4. The microscopic observation of grain geometry and mineral composition will be illustrated in Section 5. To continue, a comprehensive analysis and discussion are demonstrated in Section 6. All the key conclusions are summarized in Section 7. The findings in the paper may contribute to a better understanding the fracturing mechanisms of the rock and other brittle materials, such as ceramics and concrete.

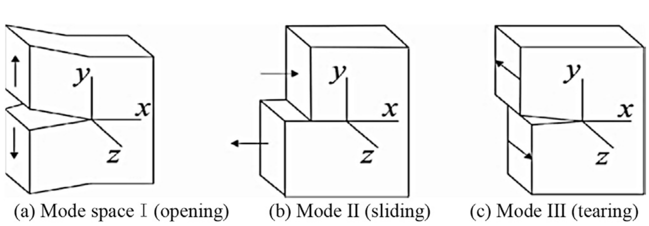

Fig. 1. Schematic illustrations of three basic fracture modes (Wu et al., 2017).

2. Comprehensive analysis procedure

This section will demonstrate the sample preparation process and the analysis procedures through a combination of MTS, DIC, SEM and EDS.

2.1. Sample preparation

In the experiments, two kinds of sandstones were tested, the Bandera Brown sandstone (BBS) and the Michigan sandstone (MS). Due to the presence of iron oxides, both of them normally show up in a reddish brown color. Taken from Kansas, BBS is known for its high contents of shaly clays, a mixture of siltstones and plants, tuffaceous fragments and casts (Sylwan, 2001; Pengra et al., 1999). Thus, it has a high tendency to swell when saturated with water based fluid. Due to its fine grain size (about 100–200 μm) and the clay fillings, it has a porosity about 20% but a very low permeability in a scale of milli-Darcy (i.e. 7 mD (Ezeakacha et al., 2017a)). Compared with the previous one, MS is famous for its larger grain size and its relatively clean composition. This kind of sandstone usually has a grain size about 250–500 μm, and the framework comprises mainly quartz, potassium feldspar, and a small amount of silicic volcanic clasts, and metamorphic (Eckert, 2000).

As indicated in the literature studies, though the sample preparation is not as stringent as others, some basic preparations are required for the application of Brazilian Test. All the important parameters are summarized in Table 1. In the experiment, after the sandstone samples were collected from the field coring operation, they were cut into disc-shaped specimens with a same 2-inch diameter, ***D,*** but different thicknesses, ***L,*** as 0.25, 0.50, 0.625 and 1.00 inches. Both the diameter error and the thickness error were controlled within 0.001 inch and 0.002 inch, respectively. After corrections on the specimen size, some discs were saturated with the local drinkable water (Lafayette tap water herein) for more than 24 h under room temperature and pressure (70 °F, 14.7 psi). As for the simulation of mud filtrated conditions, we used the discs as filters in uniaxial dynamic filter apparatus with a well-designed water based mud (added 10% fine Calcite and 1% Graphite (Ezeakacha et al., 2017b)), as shown in Fig. 2. This process was accomplished with a rotary speed of 100 RPM under a pressure differential, ΔP, of 100 psi and a temperature of 100 °F for 1.5 h. In addition, to compare the strength contrast, we also dried specimens for about 10 min under a temperature of 200 °F by vaporizing the water and not inducing new cracks. The last step of the sample preparation procedure was to coat all the tested specimens with a very thin layer of black-on-white coating on a clean face of the disc specimen, as shown in Fig. 3(c), using fine aerosol paint to achieve a high resolution and contrast for digital imaging correlation.

Table 1
Key parameters of sample preparation.

Sample Size		Specimen Drying		Static Water Saturation		Dynamic Mud Filtration			
D	L	T	Δt	Water	Δt	RPM	T	ΔP	Δt
2	0.25, 0.50, 0.625, 1.00	200	1/6	Local Tap Water	24	100	100	100	1.5

Note: where T and Δt are respectively the temperature (°F) and the time (hours) needed for a certain process.