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Given Name	Surname	Company
Alexis	Koulidis	King Abdullah University of Science and Technology
Fahd	Mohamed	King Abdullah University of Science and Technology
Shehab	Ahmed	King Abdullah University of Science and Technology

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Abstract

Challenging drilling applications and low oil prices have created a new emphasis on innovation in the industry. This research investigates the value of drill bit based force sensing at the rock-cutter interface. For this purpose, a laboratory-based mini-rig has been built in order to recreate a scaled drilling process. The work aims to build a better understanding of the collected force and torque data despite the semi-continuous drilling process. This data is then used to estimate the formation strength.

A scaled drill bit with two cutters was designed with sensors integrated into the drill bit cutter, drill string and the mini-rig structure. The mini-rig design allowed the accurate control of depth of cut by utilizing a comprehensive data acquisition and control system during the experiments. Initially, fifty-five samples were prepared with various water/gypsum ratios for a uniaxial compression test, scratch test, and for testing in the mini-rig. Prior to the mini-rig experiments, the results of the uniaxial compression and scratch tests were used as a benchmark to extract rock properties and the state of stress behavior.

The experiments under atmospheric conditions revealed that the mini-rig could accurately estimate formation strength from a few rotations. The force data at the bit-rock interface was correlated with the torque measurements, and the results indicate that the tangential force has similar trends and relatively similar values.

The groove created by the drill bit's rotating trajectory has a 14.45 cm circumference. This allows for a significant amount of data to be captured from a single rotation. The circular cutter geometry's influence is crucial for a continuous process since the active cutting area is continuously changing due to the pre-cut groove. The performed depth of cuts ranged from 0.1 to 1 mm in the same groove, and thus the active cutting area can be accurately calculated in real-time while conducting the experiments.

Tangential and normal force data from the scratch test was analyzed in order to provide insights for correlation with the mini-rig data. The analysis shows that both tests give similar trends to the force measurements from the mini-rig. Moreover, the benchmark value of formation strength that was obtained from the uniaxial compression test was also in the same range. This illustrates the potential viability of drill bit based formation strength measurement due to the similarity between mini-rig test results and those using more classical testing practices.

The experimental setup can provide a continuous cutting process that allows an accurate estimation of formation strength during a semi-continuous drilling operation with analogous application in the field. This can lead to an in-depth understanding of drilled formation properties while drilling and possibly assist in evaluating cutter wear state in-situ.

Introduction

Rock (micro) mechanical characterization is necessary to execute projects dealing with mass (Borba et al. 2014) and it takes a significant role in designing those projects. For characterization, it is important to know the deformability, the strength of rock, and other related parameters, i.e., in-situ stress (Borba et al. 2014; Cai et al. 2004). Accordingly, several tests obtain the mentioned properties, and over time, they grow and improve.

Unconfined compressive strength (UCS) is an important rock property for drilling operation optimization, wellbore stability and stress regime, before and after the drilling operations (Mostofi et al. 2011). However, the Uniaxial Compression Test used to measure these parameters, has several gaps and drawbacks, e.g., cores of intact rock are needed as well as accuracy and required time for sample preparation (Richard et al. 2012). Moisture content and irregular sample edges also have a negative influence on the results (Bieniawski 1968).

The scratch test is a method that measures the applied forces during scratching of a rock surface with a sharp or blunt cutter to estimate rock properties (Borba et al. 2014; He and Xu 2015; Joodi 2016; Richard et al. 1998; Schei et al. 2000). During the test, cutter velocity and depth of cut (DOC) are kept constant across the sample axis to create a groove (Germay et al. 2015). The test requires a perfectly flat surface for a successive recording of the tangential force (F_t) and a vertical force (F_n) of the tool to obtain a better estimation of intrinsic specific energy (ϵ), which is correlated to the formation strength (Germay et al. 2015).

Critical depth of cut separates the rock failure regime of ductile behavior and brittle behavior. Cracks initiate and propagate in an upward parabolic shape in the brittle mode, causing chipping of the rock (Hareland et al. 2007). Ductile mode occurs at a shallow depth of cut with the main characteristic of the rock's continuous shear. It has been shown that for a ductile regime, average intrinsic specific energy is equal to UCS when the back rake angle is at 15° (Richard et al. 1998), but that can change due to the combination of cutting and frictional forces that occur simultaneously (Detournay and Defourny 1992).

The restriction of extraordinary high or low cutting parameters is essential (Joodi 2016). To understand the impact of parameters on the actual specific energy, a high number of scratch tests were performed. An unconfined compression test gives the actual value of UCS (Joodi 2016) for the investigation. After several passes, the wear flat area in the cutter might appear; as a result, the sliding contact area to be higher (Gerbaud et al. 2006; Brett et al. 1989). Wear flat area might also occur in highly abrasive formations due to frictional heat (Crane et al. 2017). Because of this phenomenon, an additional friction force is acting on the wear flat area and it depends on horizontal force, vertical force and the friction coefficient heat (Richard et al. 1998; Gerbaud et al. 2006).

Related to the scratch test, several experiments have been performed to perceive the performance of a drill bit cutter (Hareland et al. 2007; Zhang et al. 2013). Some consider the chamfer size and shape, which impacts on the rate of penetration (Gerbaud et al. 2006). Due to the fact that wear flat area is parallel to the rock, chamfer, and back cutter forces disappear (Gerbaud et al. 2006). The model shows that even in a high back rake angle, it can accurately estimate the normal force.

Side rake and back rake angles affect cutter aggressiveness, and thus the mechanical specific energy (MSE) and cutting forces (Rajabov et al. 2012). The experiments were conducted at both atmospheric and confined pressure conditions, with the results showing that cutters with low back rake angles require less horizontal force to cut the same volume of the formation.

A similar experimental setup was designed by Akbari et al. (2014) to investigate the relationship of

MSE, cuttings morphology and cutter geometry. They demonstrated that an increase of chamfer length has as a result increase of MSE, but cutter size doesn't influence the required energy.

Lamik-Thonhauser et al. (2019) published a method for estimating the formation strength by calculating the cutting force required to remove a volume of rock for a vertical section. The force was calculated using the relation of the weight on bit, rotational speed and bit diameter.

Laboratory-scaled drilling rigs are developed to recreate the drilling process and enhance drilling efficiency (Drillbotics 2021). An innovative scaled cable-driven mud motor, designed by the University of Oklahoma (OU), allowed automated directional drilling with a closed-loop system (Akita et al. 2021).

Vaughn et al. (2015) show a sensing device within a cutting tool insert that can measure several parameters to monitor the condition of the cutting tool insert.

This paper aims to experimentally validate the option of integrating sensors at the bit to estimate the formation strength. Thus, the design and assembly of a mini-rig were essential to recreate the actual drilling process. This will enable real-time drilling optimization since formation strength is a major factor in the rate of penetration models (Kutas et al. 2015; Motahhari et al. 2007; Kelessidis et al. 2015).

Experimental Procedure

Sample Preparation

Since the two important parameters for rock characterization are strength and deformability (Yilmaz 2010), information about those parameters was obtained from prepared gypsum samples that hold significantly various characteristics. For gypsum samples, the water-to-gypsum (W/G) ratio influences the rock properties. In total, fifty-five samples were prepared for the unconfined compression, scratch test and mini-rig test.

The mixing procedure of the samples was as follows:

- Gypsum powder was gradually added to water and soaked for one minute to ensure saturation of the gypsum crystals (Madu et al. 2016)
- The intermixture was strongly and uniformly stirred to obtain the best possible homogeneous and consistent mass without lumps
- The ready mixture was cast into prepared PVC molds with one closed-end for the unconfined compression and scratch test, and into a unique cube aluminum design for the mini-rig test
- Simultaneous slow stick's strokes and vibrations – to minimize air bubbles inside the specimen
- Leveling upper area and filling molds
- Setting period

Results show the obvious inverse proportion of water-to-gypsum (W/G) ratio with unconfined compressive strength, i.e., one increases as the other decreases. For the current research, a random ratio was used for every mixture since the aim was to estimate the actual formation strength from all experiments.

Uniaxial Compression Test

The purpose of the uniaxial compression test was to obtain the state of stress during the uniaxial compression and evaluate the specimen's characteristics. The load rate that was applied from the syringe pump was 10 - 30 KPa/min, and the compressive strength was then calculated by dividing the maximum load by the applied area of the specimen.

Uniaxial or triaxial compression tests are the most common setups to obtain formation strength. The results were used as a benchmark for the scratch test and the mini-rig experiments.

Scratch Test

The scratch test allows several scratches to be performed to a core/sample surface under constant velocity. A load cell measures the horizontal and the tangential component of the cutting force acting on the cutter while scratching the rock surface (Richard et al. 2012). For better observation of the tangential force fluctuations, all the raw data were exported in .dat file.

In general, due to the friction term, to calculate the intrinsic specific energy, the vertical intercept of the regression has to be removed and hence the specific energy (E) and intrinsic specific energy (ε) can be expressed as:

$$E = \frac{F_t}{wd} \quad \text{and} \quad \varepsilon = \frac{F_t - \text{Intercept}}{wd} \left(\frac{d}{w} ai + 1 \right) \quad (1)$$

Where w is the cutter width and d is the depth of cut. Since all the specimens have low formation strength and the cutter is sharp, it was assumed that $E = \varepsilon$. The main reason for this assumption is that the ratio of $\frac{d}{w} ai + 1$ is close to one (where α is the angle of cutting force with respect to cutter motion (Richard et al. 1998) and i is a factor of groove geometry (Dagrain 2001)). Thus, the influence in the experiments is minor (Dagrain 2001), and it was neglected. Additionally, as published in previous work (Richard et al. 2012), the test underestimates the sample's strength for low formation strength. Therefore, by calculating and subtracting the intercept from the tangential force, the formation strength is underestimated in the result, and was therefore neglected.

Mini-Rig Design

The laboratory scaled mini-rig was designed and manufactured in-situ allowing for the recreation of the drilling environment in the lab. The data acquisition and control of the system were made with the assistance of the National InstrumentsTM LabVIEW system. The design allows an accurate depth of cut (DOC) control with an accuracy of ± 0.004 inches per foot. The drill bit rotating speed during all the experiments was predetermined at 30 revolutions per minute.

The two cutters drill bit was designed to allow the installation of sensors in one of the cutters. A miniature load cell was placed at one cutter, with back rake (BR) and side rake (SR) angle of 20 degrees and 8.06 degrees, and it was used to measure the total force (F_c) acting on the cutter (Figure 1). Additionally, the mini-rig had a torque sensor measuring the torque being applied on the bit and a load cell integrated into a unique design that was installed in a ball screw, allowing for the measurement of weight on the bit. A DC motor was connected to the ball screw, providing a precise axial movement. The motor's speed is an important parameter since by knowing the axial distance that the ball screw performs in one rotation, the DOC can be calculated at any time during the experiments.

Figure 1— Scaled two cutters drill bit design and mini-rig experimental setup

The drill bit allows a cutting circumference of approximately 14.50 centimeters, and with the sampling frequency of 1 kHz, a significant amount of data can be captured on a single rotation.

Signal processing was essential by combining a Fourier transform to decompose the signal into its frequencies and then applying a low-pass filter to remove the additional noise from other electrical devices. Figure 2 illustrates the process followed, from data acquisition and noise removal, to calculate the total cutting force for the cutting interval. It can be observed that the initial voltage starts from a value greater than zero due to the procedure that the sensor is installed in the drill bit; thus, it has to be considered as the initial state. Once the experiment was completed, all the data were exported to a .csv file.

Figure 2— Signal processing procedure for electrical noise removal and calculation of total cutting force

The LabVIEW system contains warnings and the system's immediate shutdown if a measurement exceeds the maximum safety values. Due to many electronic circuits, it is crucial to know the temperature, voltage and current of the VFD in real-time in order to prevent any issues. Benchmark values were added for buckling of the drill string, AC motor torque, module temperature and output current.

The sample that was used for the mini-rig test had to be grinded in order for the rock surface to be flat for the initial rotation. Compared with the cutting area produced by square cutters, the circular active area changed after the initial rotation (Figure 3). Since the cutter had a back rake angle, to calculate the effective

DOC's correct height in the cutter, the DOC needed to be divided by $\cos(BR)$. To calculate the active cutting area, the circular segment theory was used.

Figure 3— Active cutting area while performing a second rotation in an existing groove

During the experiments, to calculate the active area, the previous groove must be considered (Dagrain 2001). By assuming the second rotation occurred, the active cutting area could then be calculated:

$$Area_{active} = A_i - A_{i-1} \quad (2)$$

The miniature load cell measures the total cutting force acting on the cutter, and in order to calculate the tangential force, the forces had to be separated from 3-dimensional vectors. The model is based on the fundamental assumption that the total cutting force (F_c) acts perpendicular to the cutter's face (Rajabov et al. 2012), and by separating the total force into components, the tangential force can be calculated. Because of the side rake angle, the horizontal and tangential force direction is different (Figure 4). Assuming the cutter's face before rotating the back rake and side rake angles are oriented in the x-z plane, and y-axis is the axis of the cutter; hence forces in the cutter are:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} 0 \\ F_c \\ 0 \end{bmatrix} \quad (3)$$

Figure 4— Free body diagram illustration of a PDC cutter in 3D and 2D

Rotating the cutter by a back rake angle (Figure 4):

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(BR) & -\sin(BR) \\ 0 & \sin(BR) & \cos(BR) \end{bmatrix} \begin{bmatrix} 0 \\ F_c \\ 0 \end{bmatrix} \quad (4)$$

Following, by taking into consideration equation (4) and rotating the cutter by a side rake angle in x-y plane:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} \cos(SR) & -\sin(SR) & 0 \\ \sin(SR) & \cos(SR) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ F_c \cos(BR) \\ F_c \sin(BR) \end{bmatrix} \quad (5)$$

Thus, the tangential force and intrinsic specific energy:

$$F_t = F_c \cos(SR) \cos(BR) \text{ and } \varepsilon = \frac{F_t}{Area_{active}} \quad (6)$$

By knowing the torque (T) from the torque sensor, the tangential force can be re-calculated:

$$F_t = \frac{T}{r} \quad (7)$$

Where r is the distance from the center of the cutter to the center of the drill bit. The tangential force acts in the tangential direction of the rock rotation movement, which generated torque (T) on an actual drill bit (Zhang et al. 2011). Thus, the tangential force from the cutter and the torque can be correlated in single-cutter experiments.

Experimental Results

From every mixture, three individual samples were created for all three tests. Due to the limitations of the mini-rig setup, related to torque and weight on bit, the strength of the samples didn't exceed 15 MPa for the initial experiments.

The experiments were conducted in atmospheric conditions without any fluid lubricating or cleaning the drill bit from the produced cuttings. A critical stage was that all three individual samples had to be tested on the same day since the gypsum's setting period increases the sample's strength during a time interval. Also, the cutters that were used were sharp, so any friction component was neglected.

Mini-Rig

As per standard procedure, data processing was the initial step, followed by the tangential forces calculations and formation strength estimation. The molds used to create the scratch test samples had a length that was approximately 3 cm smaller than the groove's circumference that the drill bit created. Figure 5 illustrates the results of the mini-rig and scratch test. The same cutting area could not be captured due to the fact that the scaled drill bit used cylindrical cutters compared to the squared cutters of the scratch test.

Figure 5— Results showing the effectiveness of the mini-rig to estimate formation strength compare to two other testing setups

It can be observed that the formation strength variations for both tests were similar to the actual formation strength that was obtained from the uniaxial compression test. Since the samples were homogeneous, fluctuations of force measurement in particular intervals show that a small volume of gypsum was saturated differently, thus the difference in the cutting force measurement.

Regarding the torque measurements, due to the fact that the depth of cuts and the tangential forces were low, the output torque was accordingly low. Figure 6 shows the torque measurements and the calculated tangential force. In order to compare the tangential force from the torque sensor with the tangential force from the cutter (Figures 5 and 6), the experiments had to be conducted with a single cutter.

Figure 6— Tangential force calculated from the torque measurement

It can be observed that the tangential force from the torque measurements has similar trends and values as the cutter. This proves that the method of estimating the tangential force from the cutter is a promising method for the formation strength evaluation at the bit.

The results of all the test samples are illustrated in Figure 7 below. Several scratch and mini-rig tests were conducted on every sample; thus, the average from all results was taken. The results show a linear trend between the actual formation strength and the values that were obtained from the mini-rig test and scratch test.

Figure 7— Actual formation strength (UCS) versus estimated formation strength (ϵ)

Conclusions

The results illustrate a promising way of estimating formation strength at the bit under atmospheric conditions. The mini-rig design, combined with the precise control system, allows excellent data acquisition and visualization during the experiments. Depth of cut control is an essential factor in calculating the active cutting area correctly while conducting experiments.

A sensor placed at the cutter allows the measurement of the total cutting force acting on the cutter during the drilling process, which allows the interpretation of the forces to a specific cutter. The results of a series of experiments show a promising way into formation strength evaluation at the bit.

The mini-rig can accurately estimate formation strength by calculating the tangential force, thus enables the real-time optimization of drilling parameters while drilling, depending on the current ROP models.

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