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The effects of chamfer and back rake angle on PDC cutters friction

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ABSTRACT

Single PDC cutter tests at a high pressure cell were conducted and analyzed to gain an understanding of the effect of cutter geometry on its frictional response. First, sets of tests conducted with sharp non-chamfered cutters are analyzed. A decreasing trend between the friction angle and back rake angle is consistently observed. The reason can be attributed to a change in flow direction of the rock in front and near the cutting face. A linear relationship between the friction angle and cutter back rake angle is proposed. The coefficient of this relationship can be calculated using the rock internal friction angle and at least one drilling data for the given drilling fluid and contacting surfaces.

Four sets of tests with cutters of different diameters (13 and 16 mm) and chamfer lengths (0.010 and 0.016 inch) were conducted. The test results are presented and analyzed using the abovementioned semi empirical model. The method is to associate a chamfered cutter's action to an equivalent non-chamfered cutter back rake angle. It is observed that applying the test data to this analysis produces results that make physical sense with the geometric shape of a chamfered cutter.

Finally, contact stress data, for the range of back rake angles tested, confirm a strong increasing trend with back rake angle. The observations indicate that, for the conditions of these tests, that the frictional response of a cutter with developed wear flat is dominated by the wear flat friction itself.

1. Introduction

The main advantage of PDC drill bits over their counterparts, rolling cone bits, is that they do not have moving parts inside.[1] There are no journal bearing and, therefore, the issue of their failure is not the case. PDC drill bits cutting elements are the small PDC disks that are mounted on the bit body. PDC stands for Polycrystalline Diamond Compact which is an artificial type of diamond. A PDC drill bit consists of tens of such small cutting elements with careful spatial design.

To understand the action of PDC drill bits in rock cutting, one has to start with the single PDC elements. Several researchers concluded that single PDC cutter testing is a key to develop understanding about PDC bit behavior (Zijsling, 1987). This makes sense because the full action of PDC drill bit requires an integration of each single PDC cutter-rock interaction. For this purpose, several apparatuses have been developed to study the cutting action of a single PDC cutter under simulated borehole drilling conditions (Glowka, 1989; Ghoshouni and Richard, 2008; Geoffroy et al., 1998).

Many aspects regarding "performance" and "efficiency" of single cutter tests have already been under special attention (Rafatian et al., 2010; Khorshidian et al., 2012; Hareland et al., 2009). Such studies provide valuable drilling operations insight. In this article, the focus is on a better understanding of the "frictional contact" between the rock and the single PDC cutter surface. Taking advantage of several sets of experiments performed with various cutter geometries and operating conditions, makes it possible to conduct an in-depth analysis and present a coherent model.

2. Experimental facility and main parameters

The high pressure single PDC cutter testing facility at Tulsa University Drilling Research Projects (TUDRP) is capable of conducting controlled cutting experiments. The rock sample is placed and tightened above a sample holder which rotates the rock while the single PDC cutter is actuated down producing a groove on top of the rock. This system is placed inside a pressure cell which is

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[1] Recent advancements in PDC bit design include moving parts, such as the rolling PDC technology (Zhang et al., 2013).

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Nomenclature

A_c	Cross sectional area of the cut
d	Depth of cut
DOC	Depth of Cut
F_c	Cutting force
F_n	Normal force
MSE	Mechanical Specific Energy
PDC	Polycrystalline Diamond Compact
R_b	Bit radius
RPM	Revolutions Per Minute
TOB	Torque on Bit
UCS	Uniaxial Compressive Strength
WOB	Weight on Bit
β	Correlation coefficient
θ	Cutter back rake angle
θ_0	Correlation coefficient
θ_{eq}	Equivalent back rake angle
μ	Cutter-rock interface friction coefficient
φ	Rock internal friction angle
ψ	Apparent interfacial friction angle

capable of holding pressures up to 25,000 psi. Depth of Cut (DOC), Rotary speed (RPM), confining pressure, and pore pressure can be set for a test; cutter parameters such as cutter size, back rake angle and side rake angle can also be set. The fluid for the tests was mineral oil due to its low chemical activity and also its stable physical properties.

The main outputs of an experiment are the forces as shown in Fig. 1. Other outputs such as visual inspection of the cuttings (Rafatian et al., 2010), and cuttings grain size distribution (Akbari, 2014), and heat transfer and surroundings temperature (Tammineni, 2009) can also be obtained. In this article, we are only concerned with the force outputs.

The Mechanical Specific Energy (MSE) concept was introduced for a full PDC drill bit in the beginning. For a single PDC cutter system as the one described here, MSE has the same definition; however, the formulation is different. One of the fundamental differences is that there is no relative motion in the vertical direction, except the initial actuation of the cutter. The only force that is doing work is the cutting force and therefore the following equation can be written for the MSE of this system.

$$MSE = F_c/A_c \tag{1}$$

where, F_c is the cutting force and A_c is the cross sectional area of the cut.

Another important output is the interface friction angle. This is the angle that resultant force on the cutter surface makes with the normal to the surface. Note that the forces acting from the rock on the cutter surface are decomposed into two vectors in Fig. 2: tangent contact force, and normal contact force. These forces, however, are not directly measured. In terms of cutting and normal forces measured here, the interface friction angle can be written as shown below.

$$F_n/F_c = \tan(\theta+\psi) \;\; \Rightarrow \psi = Arc\tan(F_n/F_c) - \theta \tag{2}$$

where, ψ is the friction angle between cutter face and rock, F_n and F_c are the normal and cutting force components, respectively; and θ is the cutter back rake angle. This equation can be derived from a simple force balance on the cutter face along with Amonton's second law of dry friction. The relationship is also illustrated in the figure below. Please note that many assumptions have been made for this simplified model, for a complete list of assumptions please see Akbari, 2014 (pp. 96–97).

3. Friction analysis

The results of tests on sharp and chamfered cutters are analyzed here. These tests are the results of several years of testing various rock samples at atmospheric and elevated pressures on different geometry cutters making deep and shallow cuts.

This section develops in the following manner:

1) Initially, the frictional response of sharp cutters with varying back rake angles is analyzed. A semi empirical friction model is developed based on the results for a sharp cutter.
2) Subsequently, chamfered cutters are analyzed. The semi empirical model for sharp cutters is used to develop an equivalency logic between chamfered cutters and sharp cutters. Empirical data are analyzed; however, unlike the case for sharp cutters, a "model" is not proposed.
3) Finally, using the observed trends and current literature, an extension to cutters with developed wear flat is made.

3.1. Sharp cutter

Fig. 3 shows the results of experiments with sharp (non-chamfered) cutters of varying back rake angles at atmospheric pressure on two different rock samples. All the tests were performed at approximately 60 RPM rotary speed which is equivalent to 26.8 cm/s of linear cutter speed. The confining medium for these tests was air. For the tests on Mancos Shale, the depth of cut varies in an interval of 1.0 mm–1.2 mm (0.040 inch–0.050 inch). For the tests on Carthage Marble, the depth of cut varies in an interval of 0.9 mm–1.1 mm (0.035 inch–0.045 inch).

This indicates that, at least for the rocks tested, there is a strong dependency between these two parameters. The following relationship is proposed:

$$\psi = \beta(\theta_0 - \theta) \tag{3}$$

where β and θ_0 are correlation coefficients. An immediate question is that if the rock and cutter material remain unchanged, how is it possible that the friction angle varies; particularly with such significant measures? A research project by Richard (1999) proposed an answer to this question. The explanation is that the flow regime of the rock ahead of the cutter face is not necessarily entirely forward. In fact, as the cutter back rake angle increases, a resultant downward force makes a portion of the rock material flow underneath. The concept is illustrated in Fig. 4. Please note that this figure is for illustration purposes only).

Therefore, the friction factor seen in equation (2) is the result of the two opposing friction forces, which is why it "seems" to be decreasing. For this reason, it is proposed to call this parameter apparent friction angle; in this paper, we drop the word "apparent" because this is the only parameter under study. Another argument supporting this claim is the extreme case of a horizontal slider (perhaps, equivalent to a hypothetical sharp cutter of nearly 90° back rake angle). In this case, the contacting rock material, flows backward relative to the cutter advancement direction.[2]

[2] Please note again that in this context, "backward" flow is defined only for back rake angles between 0 and 90°. The definition is any rock material flow that brings it closer to the cutter bottom rather than the top. Note that this definition is meaningless if the back rake angle is exactly 90°. In the discussion, 90° back rake angle implies infinitesimally less than 90°, but not exactly.