THE AFFECT OF DIFFERENTIAL PRESSURE ON MECHANICAL SPECIFIC ENERGY DURING DRILLING WITH PDC BITS

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ABSTRACT

This paper presents the investigations on rock cutting with a PDC cutter in two different rocks. One set of experiments was performed in the artificial equivalent rock and at the atmospheric conditions. Second set of experiments was performed in Buxy limestone under simulated downhole conditions. The formation of crushed zone and propagation of cracks at the different depth of cut have been observed in detail on the equivalent rock. Then, based on the additional data from the experiment made under simulated downhole conditions, a cutting mechanism model is proposed.

INTRODUCTION

The stress state and crack propagation behavior involved in the rock cutting process is complex and have not been extensively researched. There is a need for improved understanding of the stress state and crack propagation behavior due to cutting in order to design desirable cutting tools and to achieve higher rock drilling efficiency, and/or lower energy consumption.

Several physical models of rock cutting mechanism with the PDC bit have been proposed based on the experimental study and finite element analysis [1, 2]. It is well known that the process of rock fracture under the PDC cutter generally includes the following stages: building up the stress filed, formation of an inelastic deformation zone or a crushed zone, formation of subsurface cracks, chipping and crater deformation of surface [3,4,5]. But there are some differences between the research results relating to the formation of crushed zone and the formation and propagation of cracks and chipping. Evans [6] postulated that the chipping crack is formed by the action of tensile stress. Gray [7] considered that the chipping trajectory takes a logarithmic contour and the initial cracks are formed by shear stress. Hood [8] indicated that the cutting tool induces tensile cracks in the rock and these cracks propagate to form fragments or rock chips, and the wedging action of sharp drag bits produces tensile stress in the rock in a fairly direct manner. There are also researchers that think the chipping crack is a mixed tensile and shear mode crack [5]. Zeuch [9] indicated that fractures are nucleated in the rock in advance of the cutter tip and all of the large chips had an apparently crushed, powdered region at the trailing edge of the fragment which might represent the region of intense tri-axial compression. Generally, some researchers consider that the crushed zone forms before the formation of the cone crack and its formation results from the accumulation of crushed rock between the tool and the loaded rock; others hypothesized that the size of the crushed zone is determined by bifurcation of a shear crack into tensile crack under mixed mode of loading conditions.

In this paper, the results of rock cutting with single PDC cutter has been investigated in order to propose the model of rock destruction during drilling with PDC bit.

EXPERIMENTAL PROCEDURE

First set of experiments was performed with a single squared ceramic cutter in the equivalent isotropic material prepared by mixing 36% by weight of water, 24% by weight of gypsum and 40% by weight of chalk. Mechanical properties of the equivalent material were the following. Unconfined compressive strength =0.592 MPa, tensile strength = 0.085 MPa, angle of internal friction 21.5 deg., Cohesion 1.59 bar. The ceramic squared cutters with a width of 2, 4, 6, 8, and 10 mm and back angles of -5, 0, 5, and 25 deg. The cutters were moved with constant increase of horizontal force equal to 0.369 kg/min. At the moment of chip creation, the magnitudes of the axial and tangential forces were recorded and both the chip and crater were measured as shown in Figures 1, 2 and 3.

Second set of the experiments was performed under simulated downhole overburden, confinement and overburden pressures. Three components of the cutting force were measured during the laboratory tests on a “Single Cutter Tester” stand: the axial force (F_a), perpendicular to the direction of rock cutting: the tangential force (F_t), parallel to the direction of rock cutting and the radial force (F_r), perpendicular to the direction of rock cutting and parallel to the radius of cutter rotation. The geometry of a single circular PDC cutter was characterized by its diameter and cutting angles, i.e,, back and side rake angles [10].

Impermeable Buxy limestone was used for these tests having a uniaxial compressive strength of 105 MPa, a cohesion of 40 MPa and an angle of internal friction of 40°. All tests were conducted with one type of circular PDC cutter of 1.33 cm in diameter and with a constant position, i.e., back rake angle equal to 15 degrees and side rake angle equal to O degree, A constant rotary speed equal to 120 rpm was chosen for all tests with a PDC cutter placed at a constant radius of rotation equal to 4.75 cm. The confining pressure was kept constant and equal to 50 MPa while the wellbore pressure was varied between 0 and 45 MPa. For each value of wellbore pressure, several tests with increasing depth of cut were performed. The depth of cut, constant during each one test was varied between 0.2 mm and approximately 0.75 mm. Geostatic pressure exerted on the rock sample depended on the confining pressure and was kept constant and equal to 2.57 times the confining pressure.

Data interpretation was based on the average values calculated for each single rotation. Thus, for each test three components of the cutting force and their amplitudes were obtained, corresponding to a given depth of cut and wellbore pressure. The analysis is based on the results of 90 tests conducted in Buxy limestone.

EXPERIMENTS DATA ANALYSIS

The observations and analysis of the results obtained during the first set of the experiments indicated that for the depth of cut 2mm and 4mm, the volume of a chip is smaller than the volume of rock destroyed by the cutter movement, means that the crushed/compressed zone was significantly bigger then chip volume. For the depth of cut higher than 4 mm, this ratio was reverse; means the volume of chip was bigger than volume of compressed zone and was increasing with an increase of depth of cut.

The data analysis from a second set of experiments revealed that the axial and tangential forces necessary to cut the rock with a given PDC cutter depend both on the depth of cut and wellbore pressure (see Figures. 4, 5 and 6). For drilling engineers interested in maximizing drilling rates and minimizing cost per drilled interval, there is a need for a quantitative and qualitative measure of the efficiency of the bit, and more generally, for the efficiency of the drilling process as a whole. Therefore, the mechanical specific energy (MSE) value that is a measure of energy required to drill a unit volume of rock has been calculated. MSE provides a relative measure of the efficiency of drilling process. Combined with knowledge of the rock compressive strength, MSE provides an absolute measure of the efficiency of the drilling process. As shown in Figure 7, MSE decreases with the decrease in depth of cut and wellbore pressure.

The radial force, rather small compared to the axial and tangential components, changes its direction from positive to negative being centripetal or centrifugal, respectively. These variations seem to be a random process up to a depth of cut equal to about 0,6 mm, For the depth of cuts above this ,value, the radial force increases and becomes positive. An increase in radial centripetal force with an increase of depth of cut reflects increasing influence of the PDC cutter path curvature resulting in an existence of a transverse horizontal component of the cutting force. This effect was demonstrated in different experiments with a single PDC cutter mounted on a lathe [11]. However, more data are required to verify these observations.

ROCK CUTTING MODELING

Based on the obtained results, theoretical considerations, and visual observations the author proposes a model of rock cutting that accounts for three main stages that occur in rock cutting. First under axial and tangential forces a rock in front of cutter is compressed. The increasing compression causes breakage of rock in a small zone ahead of cutter. This zone acts as hydrostatic pressure in a wellbore causing a rock breakage in tensile. The main fractures are oriented perpendicularly to the local minimum stress that is defined by the resultant force acting on a cutter. The lower fracture ceases due to the in situ stresses. The upper fracture breaks rock up to the surface and a chip is created. Then, or at the same time, the released chip has to move up against the wellbore pressure and a friction against the cutter. In order to calculate the critical stress in the compressed zone it was assumed that the resultant cutting force resulting in a chip formation is in a direction of a local maximum stress. Then, the wellbore and confining pressures were superimposed in order to calculate the critical stresses in the compressed zone causing rock fracturing. For simplicity (see Figure 8), it was assumed that a compressed zone is circular and the compressed/crushed rock exerts a hydrostatic pressure against the solid rock similar to wellbore pressure in a well. Thus, similarly, the critical pressure causing borehole fracture breakdown could be calculated using a formula:

$$p_{cr} = (3*\sigma_{h\min}) - \sigma_{H\max} - p_o + T_o \quad \ldots\ldots (1)$$

Where: $\sigma_{hmin} = p_w$ = minimum horizontal in situ stress; here wellbore pressure,
$\sigma_{Hmax} = p_c$ = maximum horizontal in situ stress; here confining pressure
p = pore pressure; here zero
T_o = rock tensile strength; here 56 bar

The assumed model describes the process rather qualitatively and cannot be used in this simple form. However, it seems to be premising direction of rock cutting modeling provided more detailed predictions of stress distribution in a rock be developed.

CONCLUSION

1. The presented results of laboratory rock cutting with a single ceramic cutter indicated that under ambient conditions, a compressed zone of rock is always created in front of cutter independently on the magnitude of depth of cut. This zone is located at the bottom of the created crater and below a chip. It seems that one part of a crushed zone constitutes a bottom part of a chip and a second part remains on the bottom of created crater. Also, the bigger depth of cut, the smaller ratio of total chip volume to the crushed part of chip. This is a reason for mechanical specific energy decrease observed with increasing depth of cut.

2. Assumed simplified model calculating critical stresses in a crushed zone gives a good explanation of the cutting process but does not account for the other stage of chip removal and frictional work done during cutting. This will be presented in the next paper.

3. More work should be done to derive the equations for stress distribution under PDC cutter, frictional work done by cuter, and kinetic energy used for chip removal.

LITERATURE

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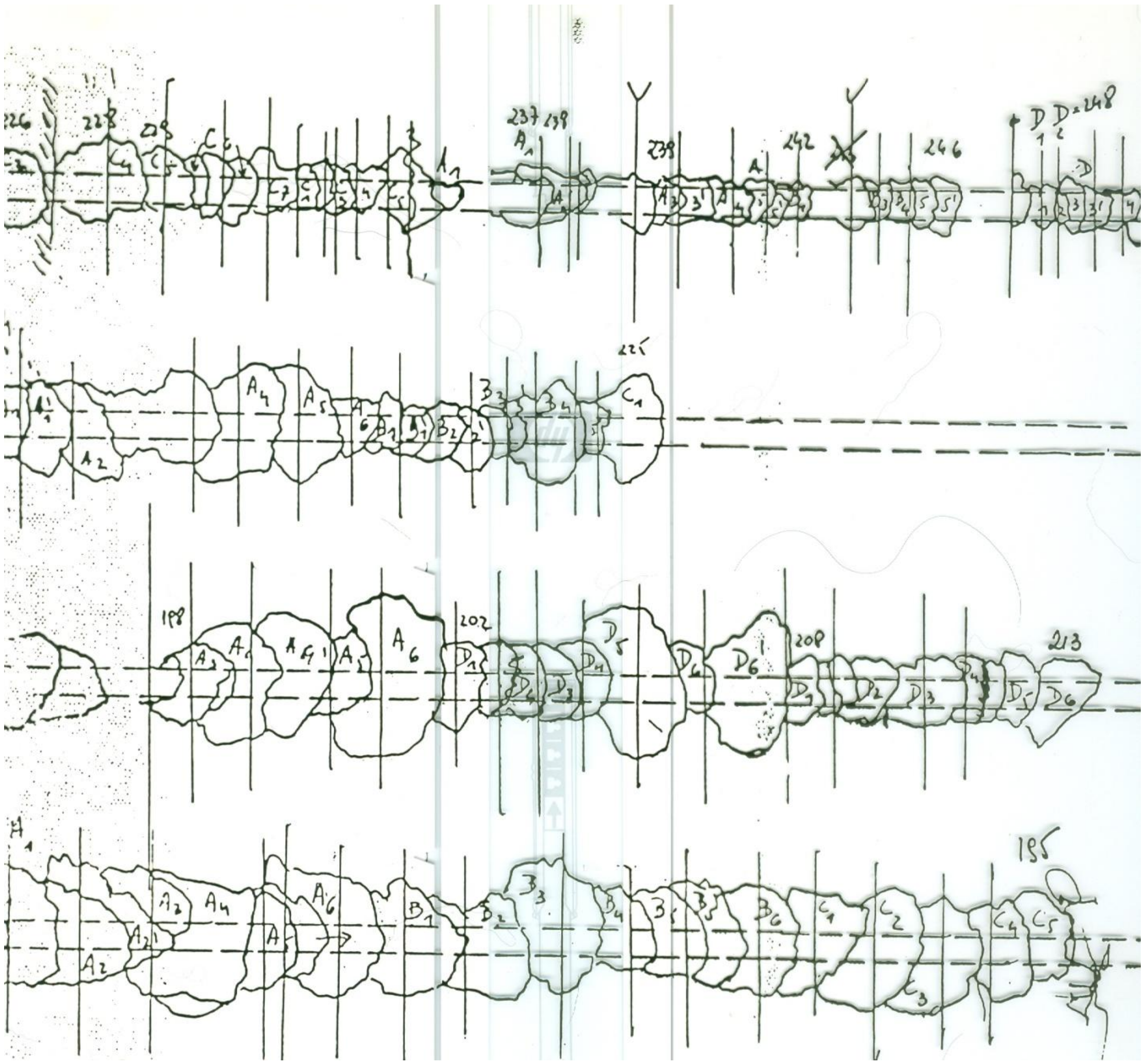

Figure 1 – Traces after rock cutting with a ceramic cutter.

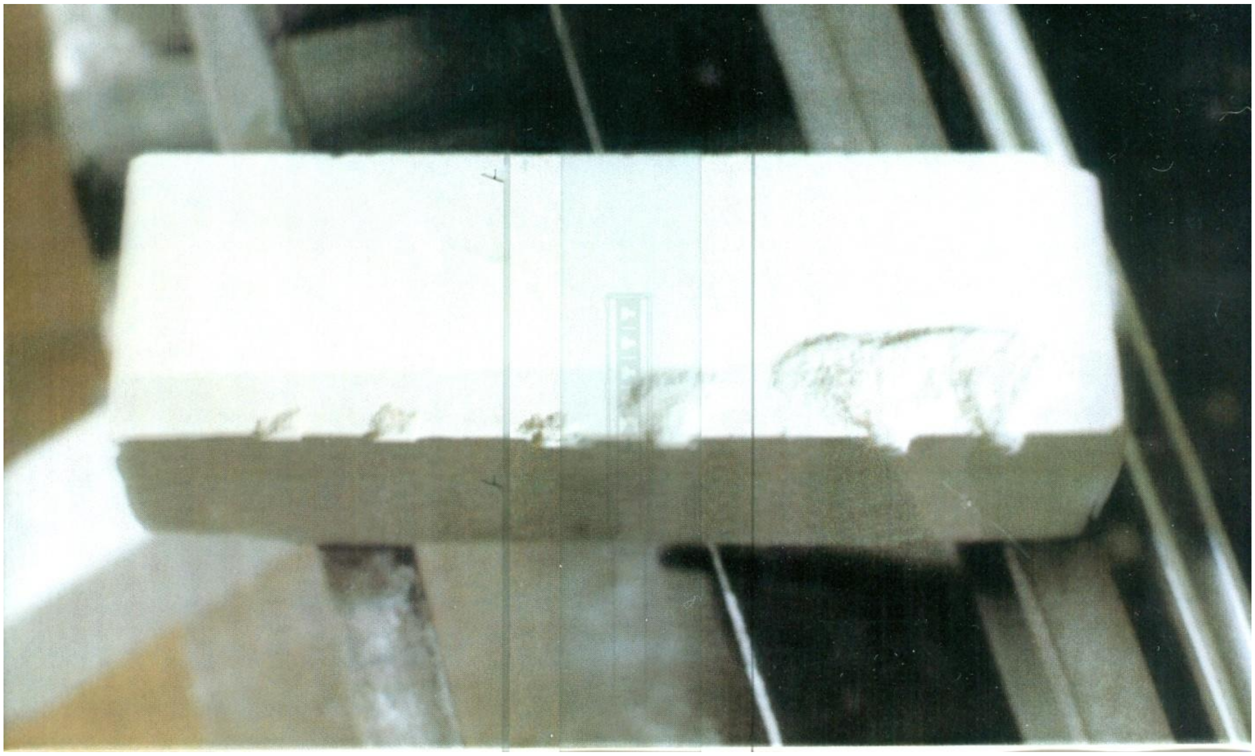

Figure 2 – The craters created by a ceramic cutter.

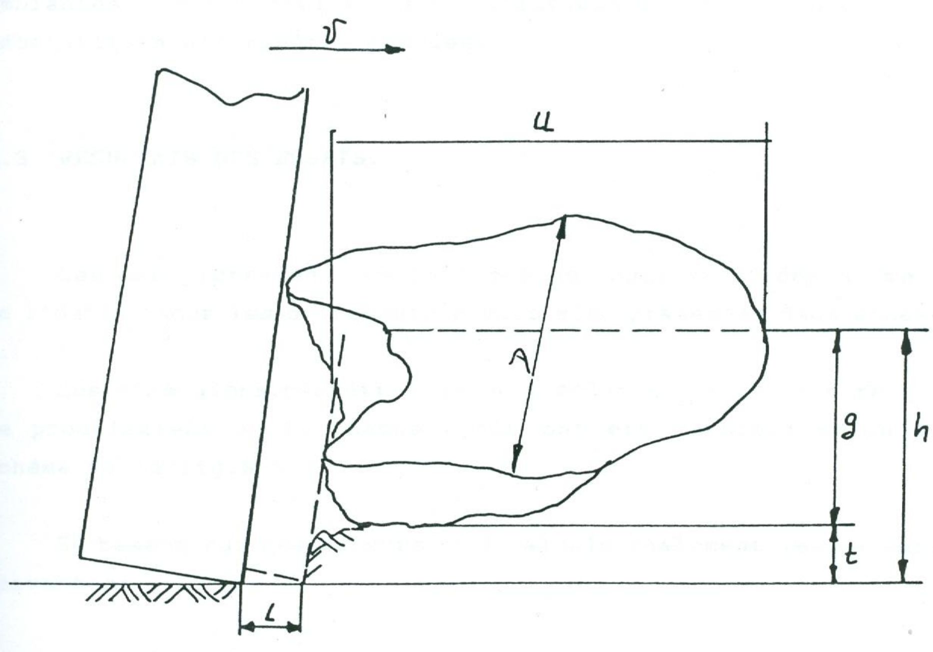

Figure 3 - Schematic of a chip and its measured dimensions.

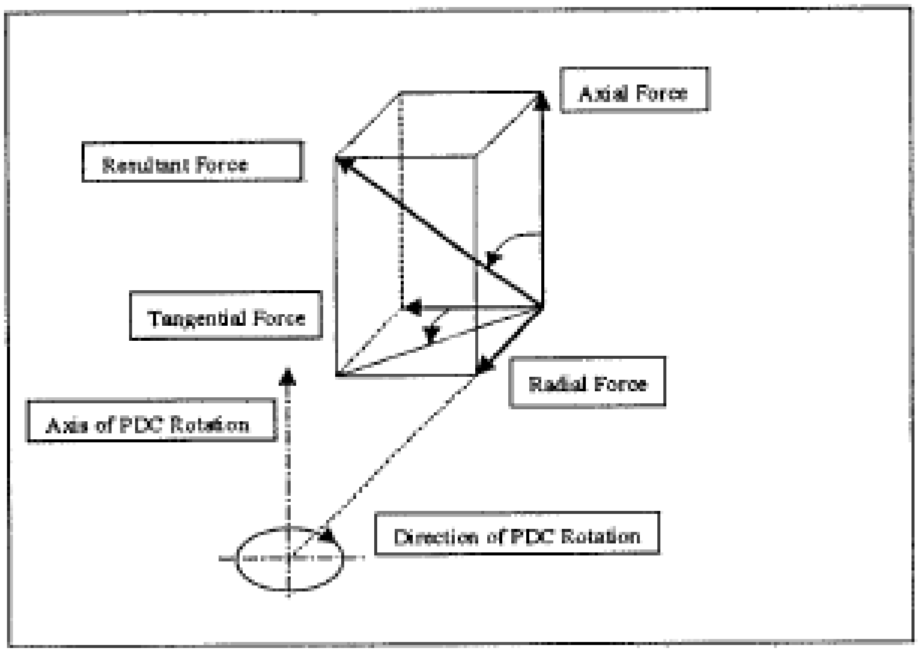

Figure 4 – Scheme of the forces acting on a single PDC cutter.

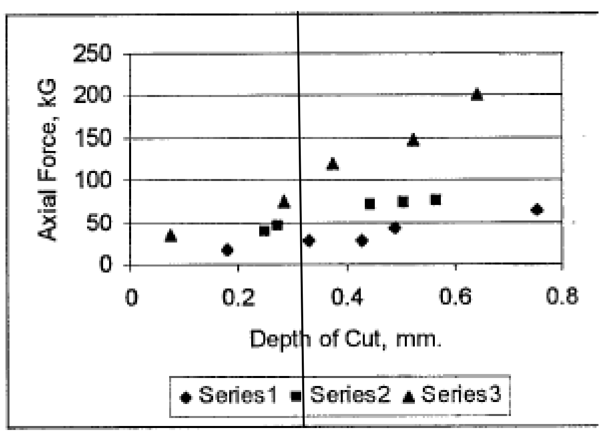

Figure 5 – Axial force vs. depth of cut. Series 1: pw = Atm, Series 2: pw=5 MPa, Series 3: pw=45 MPa.

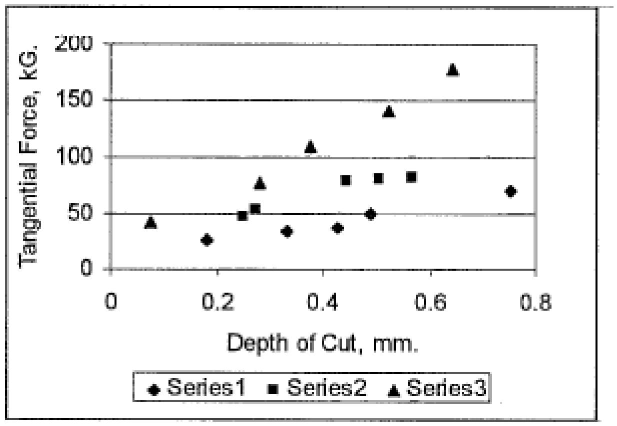

Figure 6 – Tangential force vs, depth of cut,
Series 1: pw = atm, Series 2: pw = 5Mpa, Series 3: pw = 45 MPa.

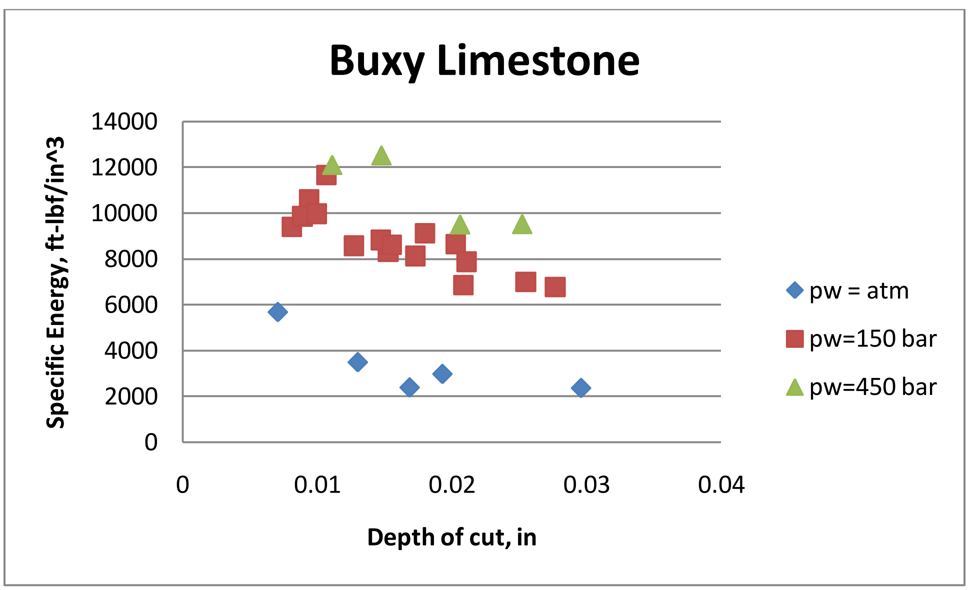

Figure 7 – Specific energy vs. depth of cut.

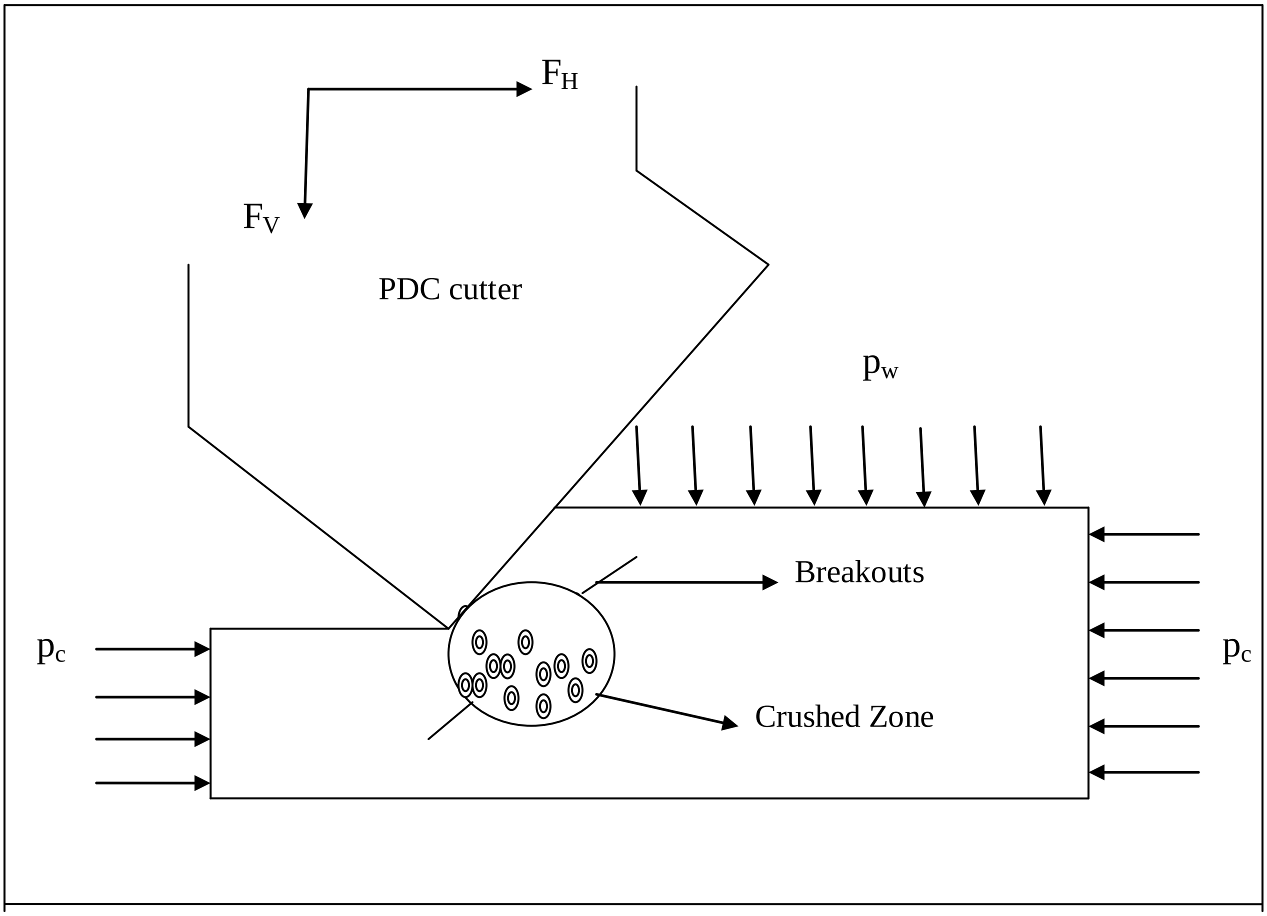

Figure 8 – Sketch of rock cutting by PDC cutter.

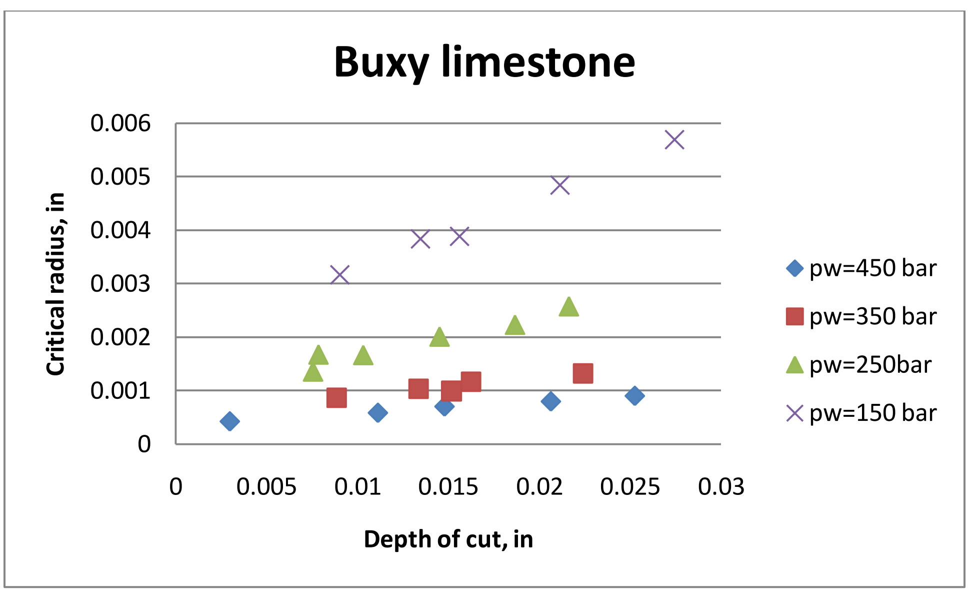

Figure 9 – Radius of crushed zone vs. depth of cut.

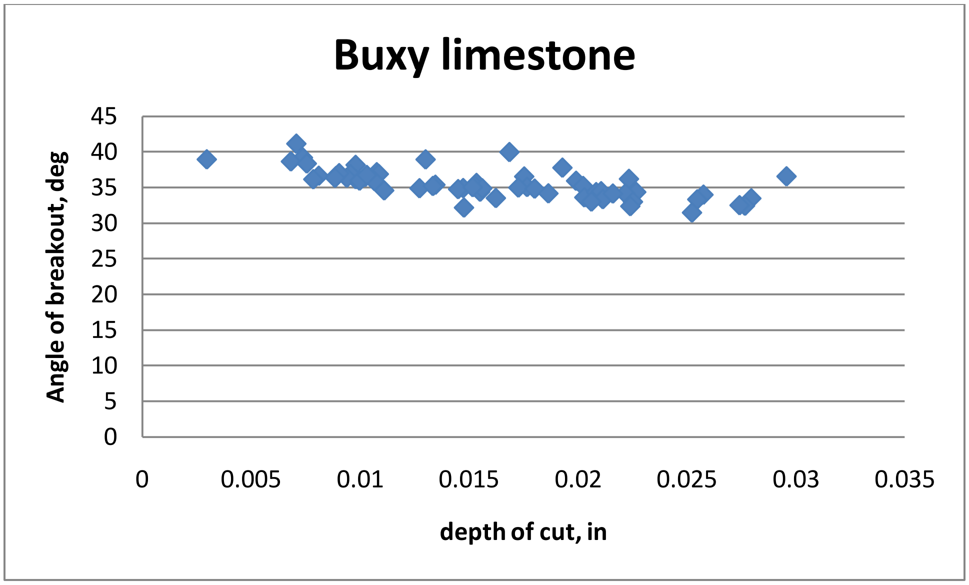

Figure 10 – Breakout angle vs. depth of cut.