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PDC SINGLE CUTTER: THE EFFECTS OF DEPTH OF CUT AND RPM UNDER SIMULATED BOREHOLE CONDITIONS

1. INTRODUCTION

As the drilling industry still suffers from low and undesirable rates of penetration in hard formations, there is an ever increasing need for better understanding of the cuter-rock interaction and the factors that affect the rate of penetration. Mechanical specific energy (MSE), the concept which is used as a measure of drilling efficiency, can be described as the amount of energy required to cut a unit volume of rock. The concept of mechanical specific energy was introduced to drilling industry by Teale (1965) [1] as the work required for removing a unit volume of rock. It is related to torque, rotary speed, weight on bit and the rate of penetration, all of which are the main parameters recorded during drilling operations.

$$MSE = \frac{480 \times Torque \times RPM}{d^2 \times ROP} + \frac{4 \times WOB}{\pi d^2} \tag{1}$$

MSE has the unit of N/m^2 or psi, which is the same unit as pressure. MSE concept has provided a way to measure the drilling efficiency by monitoring the amount of mechanical specific energy being put into the system and the minimum required specific energy to drill the rock. Lab tests performed by Teal demonstrated that the energy spent to destroy a unit volume of the rock is relatively constant, regardless of changes in ROP, WOB or RPM. Experiments have shown MSE values to be very close to the Uniaxial Compressive Strength (UCS) of the rock. Thus, MSE can be used as an assessment of the efficiency of the drilling action by measuring the MSE during drilling and comparing it with the rocks UCS numerically [2].

$$efficiency = \frac{UCS}{MSE} \tag{2}$$

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Recently performed atmospheric and pressurized single cutter tests at the University of Tulsa (2010) [3] showed that even at low pressure (100–200 psi) the cutting efficiency significantly decreased. A confining pressure as small as 150 psi could significantly increase the mechanical specific energy of cutting process and reduce the efficiency by half. Traditional practices suggest a nominally linear relationship between rotational speeds and rate of pe-netration. These practices do not link rotational speed with specific energy. It is hypothesized that at high rotational speeds we might see a decrease in specific energy required to cut a rock. In this paper we discuss the possible reasons and the results of experiments at various RPM and depth of cut under different borehole pressure environment. We investigate the effect of depth of cut and RPM on MSE under varying pressure environment with the use of the high pressure cell facility available at the University of Tulsa. Conducting single-cutter tests under controlled environments provides the industry with invaluable information regarding the cutter-rock interaction that cannot be easily obtained through full scale experimentation.

2. EXPERIMENTAL

The high-pressure cell facility at The University of Tulsa North Campus (Fig. 1) was used for performing single cutter experimentations under varying pressurized environments, RPM and depth of cut. The high-pressure test facility is comprised of 5 modules: pressure cell, pressure supplying system, rotary system, cutter engagement system and data acquisition system.

Fig. 1. High pressure cell at The University of Tulsa

The pressure cell is capable of exerting borehole pressure, which is the same as the confining pressure in the experimentation. A sample holder containing the rock sample is placed inside the pressure cell and connected to the rotary system through a shaft. The rotary system is comprised of a 10 horsepower AC motor with a gearbox to transmit the rotary power to the shaft of the sample holder. The rock sample rotates under a fixed cutter, opposite of what happens in an actual drilling operation, by a variable frequency drive to control the rotary speed. While the rock is rotating at the given rotary speed under the pressurized environment, the cutter actuation system pushes the cutter down and indents the single cutter into the rock and produces a cut in one single round of cutting. The current design of the facility is to perform almost one round of cut at a fixed depth of cut. Using a pneumatic piston for its movement, the actuation system is capable of producing up to 2800 lbs vertical force with 100 psi air pressure.

As the cutter cuts the rock sample, the forces exerted on the cutter is measured in three directions by three sets of strain gauges located above the cutter in the shaft. As depicted in Figure 2, forces acting on the cutter are measured in the direction of the cut (cutting force), in the direction of indentation (vertical force) and in the sideways direction (side force).

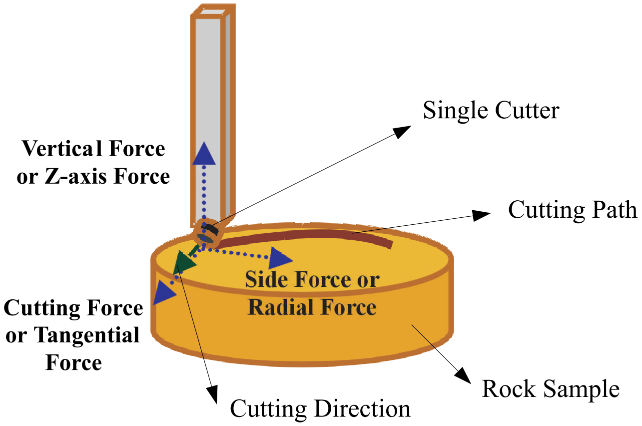

Fig. 2. Direction of forces acting on the cutter (After Rafatian [3])

A PDC cutter of 0.512 in. (13 mm) diameter with 0.017 in. 44° chamfer was used in experimentation. The cutter was brazed on a stem at 20 degrees back rake angle. The side rake angle was set as close to zero. Two types of rock samples were used in the experimentation to represent a relatively impermeable (Carthage Marble) and a relatively permeable (Indiana Limestone) formation. Carthage Marble (Fig. 3) samples were provided by Reed Hycalog, which have permeability less than 0.1 md, porosity of 1–2% and a Uniaxial Compressive Strength (UCS) in the range 9,000–11,700 psi. Indiana Limestone samples were provided by Hughes Christensen Company, which have porosities of 11–16% and permeabilities of 10–15 md. The unconfined compressive strength (UCS) of this rock is reported to be around 7,000 psi.

Fig. 3. PDC cutter used in tests (Left). A Carthage Marble (Left) and an Indiana Limestone sample (right)

With the very low permeability of the Carthage Marble, it was assumed that in all tests, the pore pressure in these rocks was very close to atmospheric. However the Indiana Limestone samples were soaked with mineral oil of viscosity 45 cp for 30 minutes prior to experimentation. The main purpose of the experiments was to investigate the effect of RPM and depth of cut under different borehole pressure on MSE. As stated earlier the side rake angle was set to zero and back rake angle was set at 20 degrees. Table 1 summarizes the test performed along with the range of parameters.

Table 1

Range of variables of the tests performed

Rock type	Confining pressure (psi)	Depth of cut (inches)	RPM	Drilling fluid
Indiana Limestone & Carthage Marble	Atmospheric, 50, 150 and 250	0.01–0.12	30–200	Mineral oil with viscosity 45 cp.

Figure 4 shows a sample of measured cutting force on the Indiana Limestone rock. This test was performed at 60 RPM, atmospheric pressure and 0.047 in. depth of cut. The plot of the cutting force/ horizontal force (F_H) vs. time indicates a spike in forces around 100 lbs, which approximately stays at its peak for 1 second (as the test is at 60 RPM). There is some inherent noise in these readings that have not been filtered. Figure 5 shows the cutting force on Carthage Marble at 180 RPM, 250 psi borehole pressure and the depth of cut was around 0.048 in. Clearly the forces spike to just over 300 lbs and stay there for around 300 milliseconds, as the test was performed at 180 RPM. Being the similar depth of cut in the both the tests, higher forces were observed on the Carthage Marble sample because the Carthage Marble is a stronger rock with UCS of 9000 – 11,700 psi as compared to Indiana Limestone with UCS – 7000 psi.

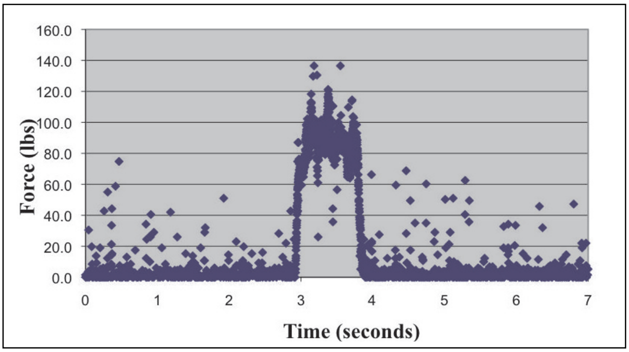

Fig. 4. Cutting Force on Indiana Limestone at 60 RPM, atmospheric pressure and 0.047 inch Depth of Cut

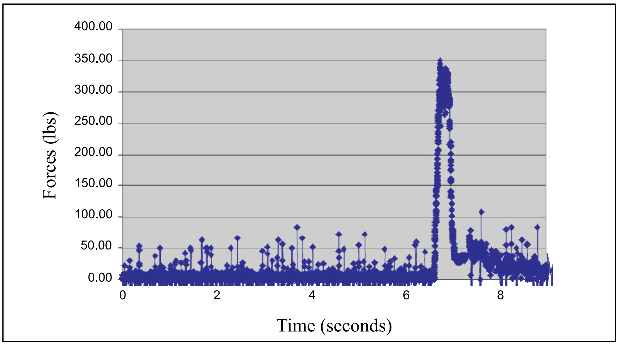

Fig. 5. Cutting force on Carthage Marble under 250 psi borehole pressure, 180 RPM and 0.048 inch Depth of Cut

Variable depths of cut obtained for various experiments result in different cutting forces making it difficult to analyze the results and make a comparison. Mechanical Specific Energy (MSE), was calculated as follows:

$$MSE = \frac{work\ \ done\ \ \ in\ \ cutting}{volume\ \ \ of\ \ rock\ \ cut} = \frac{\overline{F.\overline{ds}}}{A_c ds} \qquad (3)$$

where, *ds* is the displacement of the cutter in a circular direction. As the depth of cut is fixed, there is no work done in the vertical direction and hence MSE is merely a function of cutting force.

$$MSE = \frac{Average\ \ cutting\ \ force}{Area\ \ of\ \ cut} \tag{4}$$

Cutting forces are measured by strain gages and recorded by the data acquisition system. The data is recorded every millisecond. Hence, for a 60-RPM test there are 1000 readings and the cutting force is averaged over these readings. The area of cut is calculated through the depth of cut measured using a caliper and then taking into account the shape of the cutter. Since the cutter is at 20^{o} rake angle the area of cut is calculated considering the shape of the cutter as an ellipse. The shape of the groove cut was very consistent with the shape of the cutter.

After performing atmospheric tests, some of the cuttings would loosely stick and lump up in front of the cutter. Under pressurized conditions however ribbon shaped (saw tooth shaped) cuttings were observed stuck to the cutter (Fig. 6). These ribbon shaped cuttings, which are, saw tooth shaped on one side and very flat on the side sticking to the cutter are a characteristic of pressurized tests. It is believed that the saw tooth shape comes from a cyclical loading of the accumulated detritus on the face of the cutter. The stresses compact the detritus and become higher until they can move the cuttings up the face of the cutter and release some of the stresses where the cycle begins again.

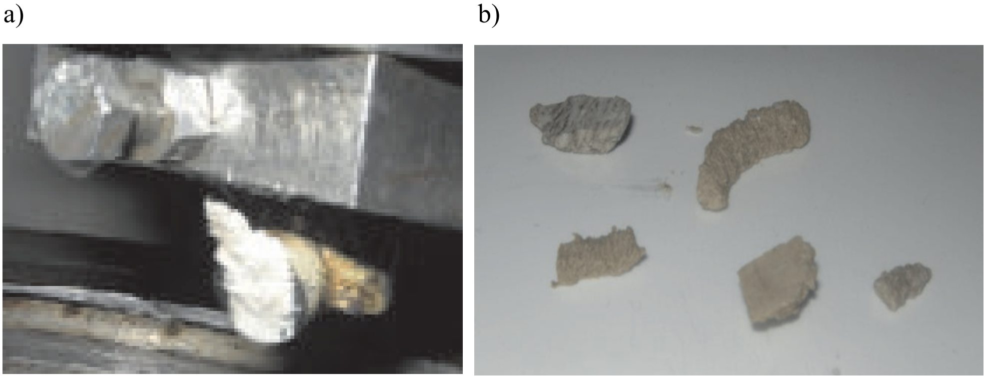

Fig. 6. Cuttings stuck to the cutter (Carthage Marble) (a), Ribbon shaped (Saw Tooth Shaped) cuttings (b)

Figure 7 shows the MSE and cutting efficiency for cutting Indiana Limestone with respect to depth of cut for different borehole pressures. The MSE required for cutting the rock decreases as depth of cut increases till about 0.08 in. depth of cut above which MSE seems to stay constant at a value close to UCS of the rock. The UCS of Indiana Limestone was known to be around 7000 psi. From the graph the MSE has a constant value for depths of cut greater than 0.08 in. which is around 7300 psi. All tests were performed at 60 RPM for atmospheric, 50, 150 and 250 psi pressure condition. With the increase in depth of cut the efficiency of cut increases. This is observed even at the increased borehole pressure but the value of efficiency is lower, as the rock strengthens under pressure. Since the efficiency is calculated as the ratio of UCS and MSE, and MSE increases with pressure, cutting efficiency will decrease as the pressure increases.

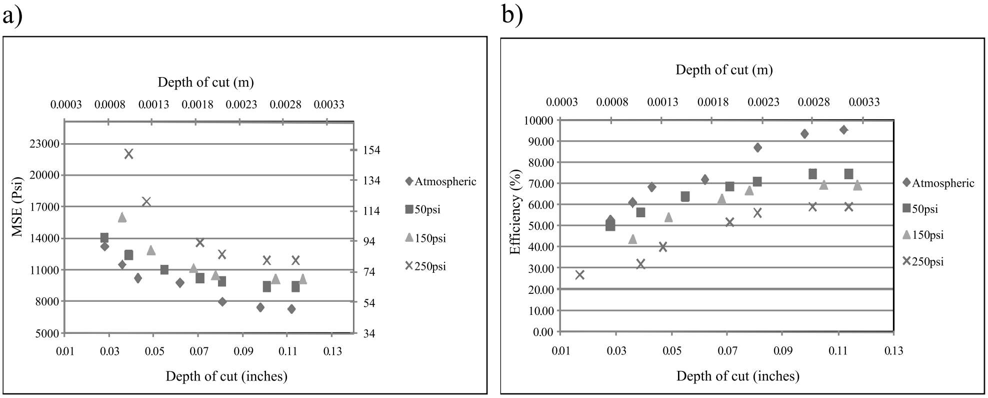

Fig. 7. MSE values (a) and efficiency of cutting (b) for Indiana Limestone as a function of depth of cut for different borehole pressure

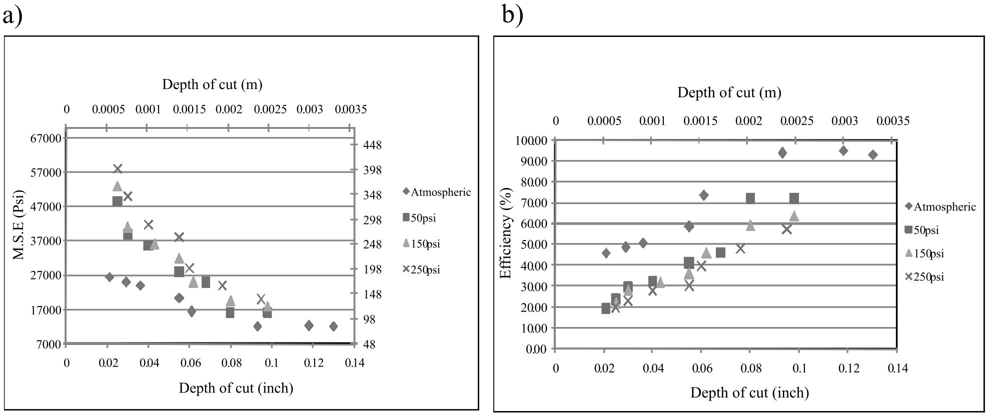

Fig. 8. MSE values (a) and efficiency of cutting (b) for Carthage Marble as a function of depth of cut for different borehole pressure

Figure 8 shows how the MSE and cutting efficiency for cutting Carthage Marble with respect to depth of cut under different borehole pressure. MSE decreases with increase in depth of cut for Carthage Marble. MSE required to cut the rock decreases with increase in depth of cut as observed for Indiana Limestone. MSE for cutting Carthage Marble decreases till about 0.08 in. depth of cut, above which it achieves a constant value close to the UCS of the rock. The UCS of Carthage Marble was known to be between 9000–11,700 psi. After about 0.08 in. depth of cut MSE stays nearly constant at 12000 psi. Under 50 psi confining pressure, after about 0.08 in. depth of cut MSE stays constant at around 15,000 psi, which is greater than the value attained with the atmospheric test, due to the fact that rock strengthens under pressure. The graph of cutting efficiency shows that efficiency increases with the increase in depth of cut under any borehole pressure conditions. At atmospheric conditions we achieved efficiency close to 100%.

There is a question left to be answered: Why does the MSE required to cut the rock decrease with increase in depth of cut? The following is a hypothesis intended to answer the above question. The shape of the cut is like an ellipse. With small depths of cut the area of cut is very small, but with a slight increase in depth of cut there is a much larger increase in width of cut and hence the area of cut. Since, MSE is the ratio of cutting force to the area of cut, at low depths of cut the area of cut being very low the value of MSE is large. As the depth of cut increases so does the area of cut, the ratio of cutting force to area of cut decreases and hence the MSE value goes down. After a certain depth of cut which was around 0.08 inch for both the rocks, the ratio of cutting force to area of cut attains a constant value i.e. UCS of the rock which results in a constant MSE. Further increase of the depth of cut, increases the area of cut in a proportion such that the MSE (ratio of cutting force/area of cut) remains constant.

Figure 9 shows how the MSE and cutting efficiency for cutting Indiana Limestone varies with respect to RPM. It appears that under atmospheric, 50 and 150 psi borehole pressure MSE stays almost constant. However, there seems to be a slight increase in MSE values with the increase in RPM, for 250 psi borehole pressure. The sizes of the cuttings were consistent for all borehole pressures and rotary speeds. The corresponding cutting efficiencies also stays constant as RPM increases, comes from the fact that MSE does not change much with the change in RPM.

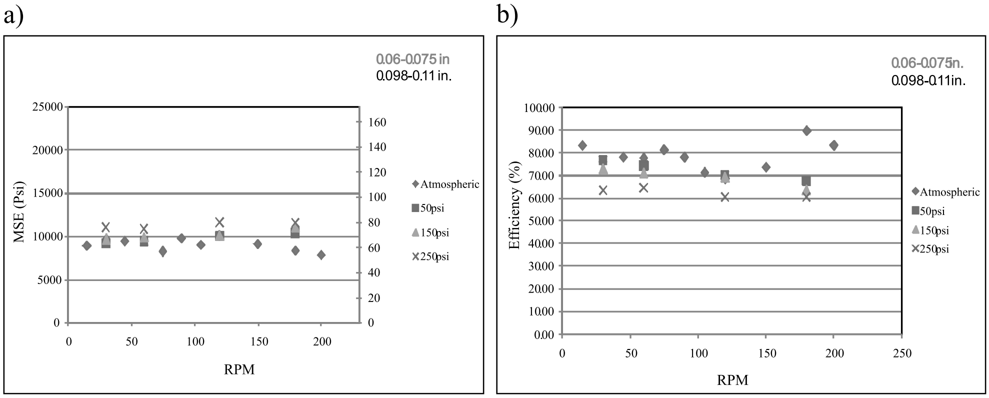

Fig. 9. MSE values (a) and efficiency of cutting (b) for Indiana Limestone as a function of RPM for varying borehole pressure conditions

Figure 10 shows how the MSE and cutting efficiency for cutting Carthage Marble with respect to RPM under various confining pressure. At atmospheric pressure conditions MSE stays constant till about 100 RPM above which MSE decreases to UCS of the rock. Efficiency increases to almost about 100% at RPM greater than 200. Similarly, at 50 and 150 psi we observe drop in MSE and increase in efficiency of cutting as RPM increased. However, the change in MSE was minor as compared to the atmospheric test. At 250 psi there seems to be no significant change in MSE with RPM.

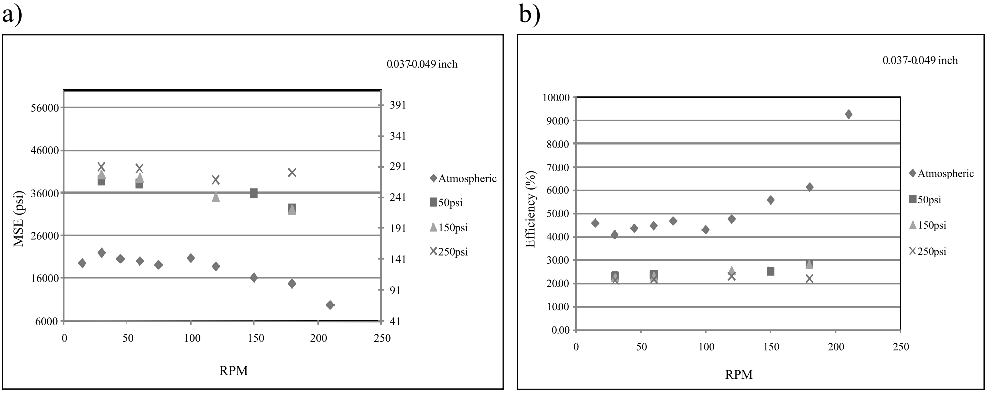

Fig. 10. MSE values (a) and efficiency of cutting (b) for tests performed on Carthage Marble as a function of RPM under varying borehole pressure

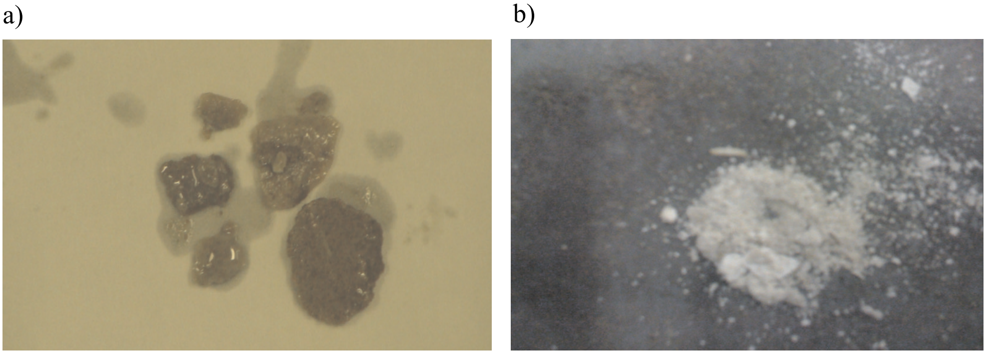

Fig. 11. Carthage Marble cuttings below 100 RPM (a) and above 100 RPM (b). (Atmospheric Pressure)

Why does the MSE decrease with increase in RPM (>100) in Carthage Marble?

The cutting action of the cutter produces chips under atmospheric pressures and ribbon shaped cutting under pressure (Fig. 11). For RPM less than 100 the cuttings generated are bigger than the powder like cuttings that observed under high RPMs (>100) and stick to the surface of the cutter. This crushed rock in front of the cutter intervenes between the cutter and the unbroken rock and becomes the means of exerting force on the unbroken rock to cut it. For rotary speeds greater than 100 the cuttings do not stick to the surface of the cutter and hence there is no intervention of the crushed material during the cutting process. This phenomenon is observed even under borehole pressure of 50 and 150 psi; however, the drop in

MSE or increase in efficiency is less than of the atmospheric test. The increase in efficiency was less than 10% as compared to the increase in 50% efficiency at atmospheric pressure conditions. However under 250 psi there seems to be no change in cutting mechanism; the size of the cuttings seems to be identical and there was no drop in MSE values as observed at pressures less than 250 psi.

Aside from the fact that this intervention of the crushed material in front of the cutter makes the cutter inefficient in cutting the unbroken rock, it also uses the compressive force intended to cut new rock to become increasingly compacted. Under atmospheric pressures it is very likely that with the slightest compaction, the crushed material find a way to go away from the surface of the cutter. However under pressure this crushed up material tends to stick to the cutter surface. This has to do with the fact that the initial compression by the face of the cutter has driven the liquid away from the space between the cutter face and the rock and when the crushed rock is produced confining pressure makes it differentially stick to the cutter. Meanwhile more rock is being crushed from the unbroken part of the rock.

MSE values were constant for experiments performed on Indiana Limestone for varying RPM and borehole pressure. This comes with the fact that no significant change in the cutting sixes observed for the experiments performed on Indiana Limestone under varying borehole pressures and rotary speeds.

Fig. 12. Indiana Limestone cuttings under varying borehole pressure and RPM

No visible change in cuttings size was observed for Indiana Limestone for rotary speeds in the range 15–210.

3. MECHANISTIC MODEL

A mechanistic model based on static balances of forces on a single cutter was proposed by Kuru and Wojtanowicz (1986) [4] that suggests a linear relationship between horizontal/ cutting forces to the vertical force/ weight on bit as:

$$F_H = mF_N + (\mu - m) R_p A_w \tag{5}$$

where, $m = \frac{(1-\mu\tan\alpha)}{\tan\alpha+\mu}$, R_p is the compressive strength of the rock, μ is the coefficient of friction, A_w is the wear area at the tip of the cutter and *á* is the rake angle (constant 20 degree). The schematic of forces on the PDC single cutter are as shown in Figure 13.

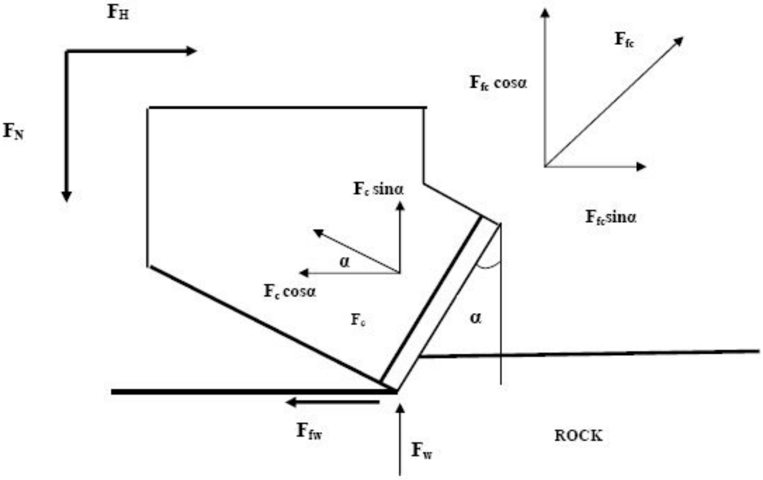

Fig. 13. Forces acting on the PDC cutter

Equations 5 suggest that the plot of horizontal force vs. normal force should be a straight line with slope, *m,* which can be obtained experimental results. While performing the experiments horizontal force/cutting force (F_H) and normal force/vertical force (F_N) were measured. The values of R_p (compressive strength of the rock) and A_w are known and measured respectively. Figure 14 shows experimental values (horizontal and vertical force acting on the cutter for experiments performed on Carthage marble and Indiana Limestone rock samples. From the equation of the lines the slope, *m*, was obtained as 0.78 and 1.72 corresponding to the friction coefficients of 0.62 and 0.18 for Carthage marble and Indiana Limestone, respectively. Data were fitted to a zero intercept line as the cutters are brand new and trivial wear was observed on the cutters after cutting process. Hence the wear area was neglected leading to a zero intercept in eq. 5. Moreover, the data from various pressure tests were combined due to the limited number of data point at a certain pressure and narrow range of depth of cut used in the experiments.

As expected the value of friction coefficient for a harder rock such as Carthage Marble (μ = 0.62) is much greater than the value obtained for a relatively softer rock such as Indiana limestone (μ = 0.18). This is due to the fact that Carthage Marble being stronger (UCS = 9000 – 11,700 psi) than Indiana Limestone (UCS = 7000 psi). The above-presented model relates the cutting force or torque to the normal force or weight on the bit (WOB). The model can be used to detect changes in formation by predicting the rock type from drilling data. The model suggest that during drilling operation, the plot of the cutting force vs. weight on bit for various rate of penetration will give a line with slope, *m*, and the intercept, *c*, which can be used to back calculate the friction coefficient, μ, and determine the type of formation as well as bit wear.

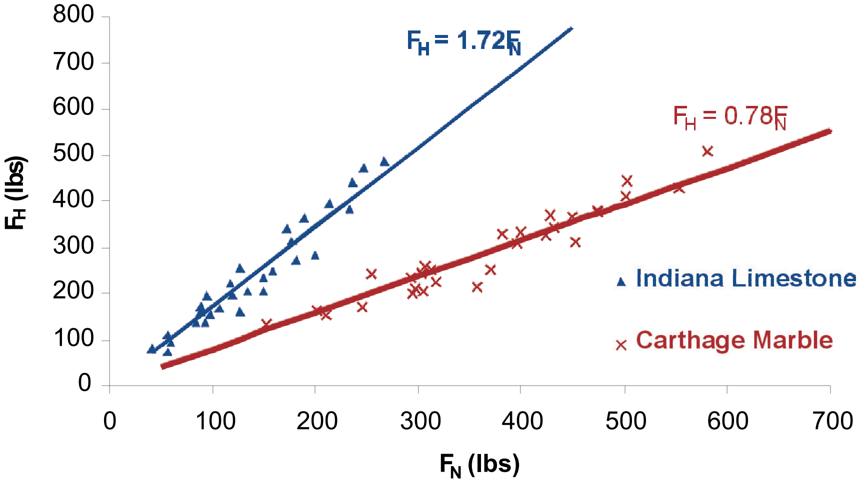

Fig. 14. Horizontal/ Cutting force (F_H) vs. Vertical/ Normal force (F_N) for tests on Indiana Limestone and Carthage Marble rock samples

4. SUMMARY

Depth of cut played an important role in increasing the drilling efficiency for both Indiana Limestone and Carthage Marble. With the increase in depth of cut MSE required to cut the rock decreased and hence the drilling efficiency increased till about 0.08 in. depth of cut. This drop in MSE values was consistently observed for all pressure conditions. There was no further increase in drilling efficiency for depths of cut greater than 0.08 in.

The observations of this study show that a rotary speed has minimal impact on the efficiency of cutting. RPM can play a role in increasing the drilling efficiency only for certain rock types and borehole pressure conditions. For instance the drilling efficiency of Carthage marble was increased by 50% when the rotary speed increased from 100 to 200 RPM. The increase in efficiency however was only around 10% for confining pressures of 50 and 150 psi. For tests under 250 psi confining pressure no significant change was observed in the drilling efficiency.

Based on the observation in this study the following conclusions can be drawn:

- Mechanical specific energy of cutting decreases with increase in depth of cut and tends to attain a constant value close to the UCS of sample tested for depths of cut greater than 0.08 in. Any increase in depth of cut after around 0.08 in. appeared to have minimal effect on the MSE values.

- In case of Indiana Limestone the MSE remained nearly constant for the rotary speeds in the range of 15– 210 under the confining pressures tested (atmospheric, 50, 150 and 250 psi).
- In case of Carthage Marble, as RPM increased the MSE stayed nearly constant till 100 RPM, but decreased by half for RPMs greater than 100 under atmospheric pressure. However, minor decrease in MSE with RPM was observed for tests under pressurized conditions.
- Powder-like cuttings observed while cutting Carthage Marble at RPM higher than 100, indicates a change in cutting mechanism. This may be one of the reasons of improved cutting efficiencies for RPM greater than 100. The powder-like cuttings did not seem to stick to the surface of the cutter in a manner the cuttings generated for rotary speeds less than 100 which piled up at the surface of the cutter and led to reduced efficiencies.

Acknowledgments

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