



Investigation on the effect of changing rotary speed and weight bit on PCD cutter wear

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Abstract

The research is to determine the optimum range of rotary speed and weight-on-bit value for interbedded formation to reduce PCD cutter wear rate. To simulate an interbedded formation, a combination of limestone as the soft formation and granite as the hard formation is selected. The research is conducted based on analysis of cutter-rock interaction model, wear model and simulation of PCD cutter using finite element analysis in ABAQUS software. The results show that the optimum range of weight on bit and rotary speed for limestone is between 1000 N, 21.4 RPM, and 4000 N, 85.6 RPM, while for granite it is between 1000 N, 21.4 RPM and 3000 N, 64.2 RPM.

Keywords Drilling · Weight on bit · Rotary speed · PDC cutter wear rate · PDC cutter · Interbedded formation · FEA · Rock-cutter interaction model · Wear model

Introduction

In oil and gas industry, it is desirable to drill to the intended depth at the shortest possible time. Such objective relies on several factors, among which are drill bit technology and drilling rate. From several available drill bit types, the polycrystalline diamond compact (PDC) bit is widely used due to its high drilling performance. Drilling rate is known as rate of penetration (ROP), and factors that optimize ROP are drilling main operation parameter such as weight on bit (WOB), drill bit rotary speed (RPM), bit hydraulics and cutter wear. PDC bit consists of multiple polycrystalline cutters (PCD) attached to a bit body, and it cuts through rock by shearing.

The project objective is to investigate the effect of changing rotary speed (RPM) and weight on bit (WOB) on PDC cutter wear as a means to improve ROP. It is assumed that

reducing PDC cutter wear rate will lead to increase in bit life and drilling rate, thus improving drilling efficiency.

Theoretical background

PDC cutter wear

For normal wear, it occurred mainly due to the abrasiveness of the formation and the effect of drilling operation parameter (Zhang et al. 2013). Higher load on the cutter causes higher wear rate (Warren and Armagost 1988), while the high rotary speed generated from the down-hole drilling motor caused broken seals, worn bearings and bit malfunction (Bruton et al. 2014). Drill bit also suffered from thermal abrasive wear and impact damage when drilling interbedded formations (Yahiaoui et al. 2013). PDC cutters will be in good condition when the wear rate happened uniformly, but once a cutter wore out rapidly compared with other cutters in the bit, thermal wear might occur and wear flat will be generated (Glowka 1987). FEA simulation as shown in Fig. 1 shows frictional heat concentrated at the cutter's wear area. Wear flat happened at the bit shoulder as the velocity of bit outer edge and the rock volume were high (Bruton et al. 2014).

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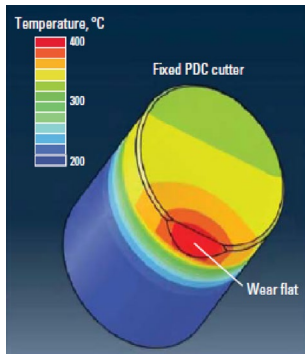


Fig. 1 Heat-induced cutter degradation in FEA (Bruton et al. 2014)

Rotary speed

Rotational speed less than 100 RPM tends to produce bigger rock cuttings. These big cuttings might crush the diamond cutter and stick to cutter surface, especially when drilling in medium formation such as Carthage Marble (Majidi, Miska and Tammineni 2011). The stucked rock cuttings caused bit balling and initiated cutter wear and degraded cutting efficiency. Thus, high rotary speed above 100 rpm was preferable for soft and medium formations (Majidi, Miska and Tammineni 2011).

For abrasive and hard formation, the relationship between bit life to weight on bit and rotary speed is shown in Eq. (1) (Zhang et al. 2013):

$$T = a\phi^b W^c e^{dN} \tag{1}$$

where T is bit life in hours, a is the bit life coefficient with a value of 9.2937×10^9 , b , c and d are the regression coefficients related to bit type. The values of $b = -3.04063$, $c = -1.24374$ and $d = -0.01867$ (Zhang et al. 2013).

Based on the relationship of bit life and rotary speed as shown in Fig. 2, the graph showed that bit life will reduce as the rotary speed increases (Zhang et al. 2013).

Rock abrasiveness and drilling operation parameter gave huge effect to bit life, especially on the formation of wear of PDC cutter (Ortega and Glowka 1982) as they were

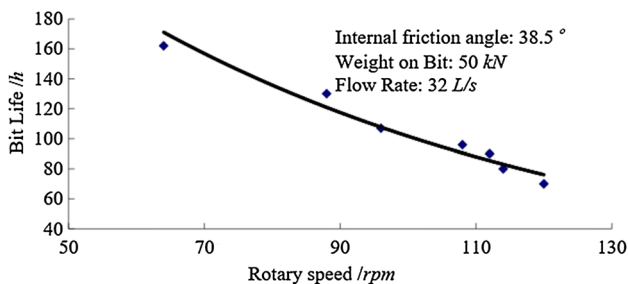


Fig. 2 Relationship of bit life (h) and rotary speed (RPM) (Zhang et al. 2013)

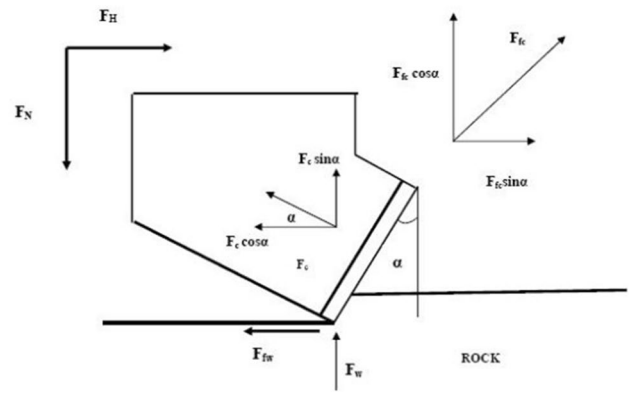


Fig. 3 The forces that act on the PDC cutter (Majidi et al. 2011)

dynamically reacted during drilling practice (Zhang et al. 2013).

Weight on bit (WOB)

The linear relationship between horizontal cutting forces and vertical force (weight on bit) is described by Eqs. (2) and (3) (Majidi et al. 2011):

$$F_H = mF_N + (\mu + m)R_p A_w \tag{2}$$

$$m = \frac{(1 - \mu \tan \alpha)}{\tan \alpha + \mu} \tag{3}$$

R_p is the rock compressive strength, μ is the coefficient of friction, A_w is the wear area, and α is the rake angle.

Figure 3 shows the horizontal and vertical forces acting on a single cutter. F_N is the weight on bit, while F_H is the cutting force needed to cut the formation (Majidi et al. 2011).

Based on Fig. 4, straight lines were produced from slope (m) value of mechanistic model. The slope value was the ratio of cutting force, F_H and weight on bit, F_N during drilling

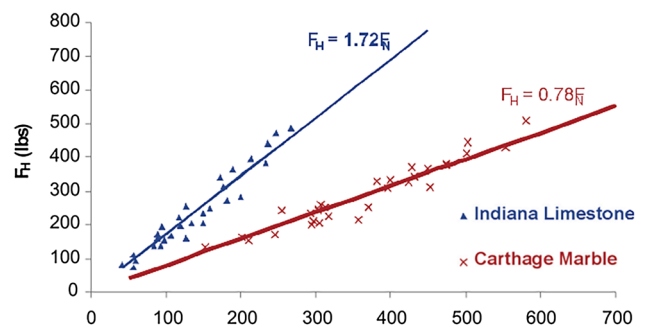


Fig. 4 Horizontal/cutting force (F_H) versus vertical/normal force (F_N) (weight on bit) for Indiana Limestone and Carthage Marble (Majidi et al. 2011)

process. The slope, m value of Indiana Limestone is steeper than that of Carthage Marble because medium hardness Carthage Marble formation needs higher weight on bit compared to soft hardness Indiana Limestone formation. It can be concluded that for normal drilling process, weight on bit acted at higher value in medium, abrasive or hard formations.

Previous research studied the effect of weight on bit on the penetration rate of PDC based on different rates of cutter wear when drilling through soft and medium hardness formations. The study compared the ROP of two new bits, one moderately worn bit and one severely worn bit which were used to drill similar depth of 1294 ft (394 m). The results show that for soft formation, higher weight on bit (WOB) on the moderately worn bit can produce drilling rate similar to the new bits, while the severely worn bit showed 70% less ROP compared to the new bits. For the medium hardness formation, both worn bits have lower ROP compared to the new bits but the moderately worn bit has better ROP compared to the severely worn bit (Warren and Armagost 1988).

Wear model

Tangena formulated a wear model to indicate the wear pattern in the deformation of the geometry (1987). The wear model is described by Eq. (4):

$$W = k_2 V \sigma \frac{1}{b n'} \quad (4)$$

where W , k_2 , V , σ , are the wear value, constant of wear, deformed value, and Von Mises stress, respectively. V is equal to $a_2 \Pi d$, where a_2 is the contact radius and d is the thickness of the layer. The proportionality constant, $k_2 V$, for polycrystalline diamond (PDC) has a value of (1.5×10^{-11}) . The constant b value is 0.5, and n' is the cyclic strain-hardening coefficient (Tangena 1987). Von Mises stress was the input of the wear model, and the relationship between Von Mises stress and wear was directly proportional to each other.

Methodology

Define parameter

There are three types of parameters for the research:

- Constant variable: back rake angle, cutter shape, feed rate size, cutter material, and type of formation.
- Independent variable: weight on bit (WOB) and rotary speed (RPM).
- Dependent variable: cutter wear rate.

Tables 1, 2 and 3 show the value of each parameter needed for analytical analysis and FEA simulation.

Basically, the penetration rate of the cutter is directly proportional to the wear rate. Thus, the decrement of ROP value with increment of RPM and WOB will show the same result for wear rate of drill cutter. Therefore, in deciding independent variable, the value of WOB and RPM will be loaded increasingly on the cutter during simulation. The value of parameter is given in Table 2 as follows.

The simulation of drill cutter with rock formation is executed in ABAQUS software. The basic rock relation was managed by Johnson–Cook law, and plastic strain was applied to evaluate the rock breaking (Adzis et al. 2018). The parameters of WC–Co and rock formation are shown in Table 3.

Analytical model

Analytical method is executed based on mathematical formula of cutter-rock interaction model, where the calculation is analyzed based on cutting face force. Using Eq. (4), the weight on bit, F_n^c and velocity, V will be the

Table 1 Constant design parameters for PDC cutter

PDC constant parameter	Variable for limestone	Variable for granite
Size of cutter	16 mm	16 mm
Material of cutter	PDC & WC–Co	PDC & WC–Co
Diamond carbide interface	Conventional	Conventional
Side rake angle	0°	0°
Back rake angle	30°	30°
Shape of cutter	Beveled	Beveled
Rock-cutter friction angle	33°–40°	31°–40°
Surface area of cutting face, A	$3.1163 \times 10^{-4} \text{ m}^2$	$3.1163 \times 10^{-4} \text{ m}^2$
Shear contact area, AS	$1.5582 \times 10^{-4} \text{ m}^2$	$1.5582 \times 10^{-4} \text{ m}^2$

Table 2 The list of WOB and RPM values

Run	Weight on bit	Rotary speed
1	1000	21.4
2	2000	42.9
3	3000	64.2
4	4000	85.6
5	5000	107.0
6	6000	128.4
7	7000	149.8

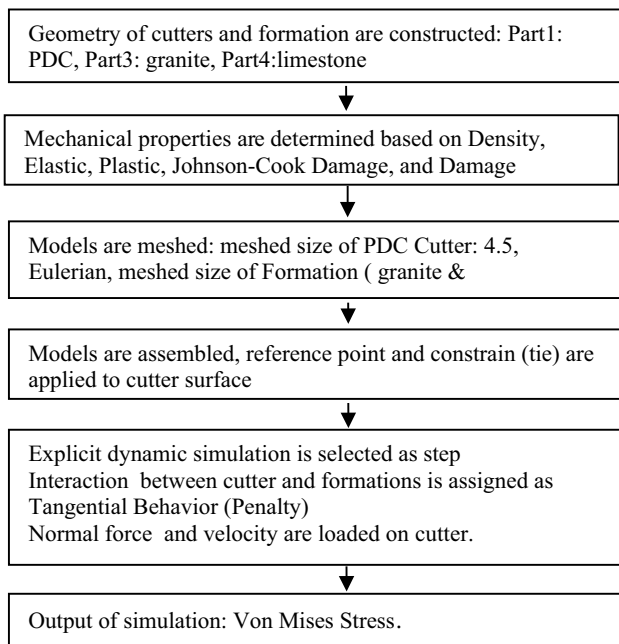
Table 3 Model parameter of PDC and rock formation

Material Properties	Limestone	Granite	PDC
Unconfined compressive strength, UCS (MPa)	50	300	–
Density, ρ (kg m ⁻³)	1580	26200	3510
Ultimate tensile strength, UTS (MPa)	2.5	256	–
Shear yield stress (Mpa)	5	132	–
Young's modulus, E (Gpa)	3.2	70	890
Poisson ratio	0.1447	0.30	0.07
Kinetic coefficient, μ_k	0.6223	0.45	–
Strength parameter A (MPa)	-8.93	0.79	4000
Strength parameter B (MPa)	0.012	1.60	500
Strength parameter n	1566.99	0.007	0.14
Damage parameter D_1	0.040	0.040	0.05
Damage parameter D_2	1	1	1.873
Damage parameter D_3	–	–	-2.272

input in order to generate the output such as intrinsic specific energy, horizontal force, axial and shear stress of cutter test formula.

FEA

The simulation of explicit dynamic is executed in ABAQUS by loading weight on bit and linear velocity on PDC cutter based on constant and independent parameter for granite and limestone. The simulation of PDC cutter in ABAQUS software has been executed as shown in Fig. 5.

**Fig. 5** FEA flowchart

Results and discussion

Based on the analytical result, the horizontal forces increase with the increment of weight on bit and rotary speed that act on the PDC cutter. The increase in intrinsic specific energy and horizontal force will rise axial and shear stress directly, and at one point, the excess value of intrinsic specific energy and horizontal force will produce maximum total stress that will cause cutter wear to happen. In addition, the values of intrinsic specific energy and horizontal force for granite as shown in Table 4 are higher compared to those of limestone. The result shows that hard and abrasive formation is one of the factors that cause intrinsic specific energy and horizontal force to rise.

The result in Table 4 shows that analytical stress, axial stress, shears stress and intrinsic specific energy values rise linearly with the increment of WOB and RPM, and the maximum stresses are generated at 7000 N of weight on bit and 149.8 rpm of rotary speed. Axial stress increases because of the rise of weight on bit while, the increment of shear stress and intrinsic specific energy occurs when the value of rotary speed and horizontal force are added from the first to the seventh step of the run.

The result shows that axial stress that acts on granite has same value with limestone, but for shear stress, its value is larger compared to shear stress in limestone. It happens because the horizontal force for granite is higher than that in limestone for each run. Thus, hard and abrasive formation such as granite is proven to generate higher shear and total stress than soft formation. In conclusion, the wear rate of PDC cutter in granite directly will be higher than that in limestone.

The results in the last two columns in Table 5 refer to the result from ABAQUS simulations. The table shows different patterns from the analytical result, where for limestone the

Table 4 Intrinsic specific energy and horizontal force for independent parameter of single cutter test for granite

Variable		Limestone		Granite	
Weight on bit, F_N (N)	Rotary speed, V (rpm)	Intrinsic specific energy, R_{eq} (MPa)	Horizontal force, F_H (N)	Intrinsic specific energy (MPa)	Horizontal force (N)
1000	21.4	13	511	14	550
2000	42.9	26	1022	28	1101
3000	64.2	39	1533	42	1651
4000	85.6	52	2044	56	2201
5000	107.0	65	2555	71	2791
6000	128.4	78	3066	85	3341
7000	149.8	91	3577	99	3891

stress starts to increase from the first run to the fourth run. Then, the stress drops in the fifth and seventh runs except for the sixth run as it increases in value at small amounts.

The stress increases in big scale at the first until the fourth run because at these times, horizontal forces are generated increasingly in order to cut the formation. Once the formation is cut, the generated energy will be lesser, and at the maximum point of simulated stress, the wear of cutter is produced. The output of the simulation for granite shows different patterns where the stress starts to increase from the first run to the third run. The stress increases slowly before it decreases from the fourth run to the seventh run.

Table 5 Calculated stresses for independent parameter of single cutter

Run	Variable	Limestone	Granite	Limestone	Granite
	Weight on bit, F_N (N)	Analytical stress (MPa)	Analytical stress (MPa)	Simulated stress (MPa)	Simulated stress (MPa)
1	1000	6.49	6.74	2.557	5.111
2	2000	12.98	13.49	5.663	5.241
3	3000	19.46	20.22	10.850	11.010
4	4000	25.96	26.97	17.270	6.292
5	5000	32.44	33.95	9.5480	9.870
6	6000	38.93	40.69	11.300	4.153
7	7000	45.42	47.43	4.377	13.54

Table 6 Wear values of PDC cutter

Weight on bit, F_N (N)	Limestone	Limestone	Granite	Granite
	Analytical wear (m^2)	Simulated wear (m^2)	Analytical wear (m^2)	Simulated wear (m^2)
1000	6.28×10^{-4}	2.48×10^{-4}	6.52×10^{-4}	4.94×10^{-4}
2000	1.26×10^{-3}	5.48×10^{-4}	1.31×10^{-3}	5.07×10^{-4}
3000	1.88×10^{-3}	1.05×10^{-3}	1.96×10^{-3}	1.07×10^{-3}
4000	2.51×10^{-3}	1.67×10^{-3}	2.61×10^{-3}	6.09×10^{-3}
5000	3.14×10^{-3}	9.24×10^{-4}	3.28×10^{-3}	9.54×10^{-4}
6000	3.76×10^{-3}	1.09×10^{-3}	3.94×10^{-3}	4.02×10^{-3}
7000	4.39×10^{-3}	4.23×10^{-4}	4.59×10^{-3}	1.31×10^{-3}

The stress increases in big scale at the first until the third run as horizontal force is generated increasingly in order to cut the formation. Its values are not constant after the fourth run because for hard formation, the cutter might be unstable as the vibration occurs with the increment of WOB and RPM during drilling process. The instability of cutter will initiate unstable and different values of ROP and it causes generated Von Mises stress to be increased and decreased simultaneously. The same situation happens in limestone after the fourth run, but the value of simulated stress is lower. At the maximum value of WOB, RPM and F_H , the generated Von Mises stress is at the maximum value. At the maximum point of simulated stress, the wear of cutter might be produced. The wear rate is determined for limestone and granite separately, and the wear value of PDC cutter for granite and limestone is shown in Table 6.

The wear area of PDC cutter from analytical method is increasing with the increment of analytical stress, while for simulation method the wear areas are not consistent for granite and limestone. It occurs because of the same drilling failures such as vibration and cutter bouncing where they are produced from the effect of slip–stick action, broken formation, and pump-off force. Comparing both formations, it can be seen that the wear rate of PDC cutter for granite is bigger than that for limestone. This is because the higher stress in granite had speeded up the rate of wear of PDC cutter.

Conclusion and recommendation

From analytical analysis, high weight on bit and rotary speed produce high horizontal force, intrinsic specific energy and stress on PDC cutter, but in finite element analysis, the increment value of these parameter produces inconsistent value of horizontal force, intrinsic specific energy and stress on PDC cutter. The main cause is because of instability of PDC cutter from vibration during simulation. The excess unstable mode of cutter initiates bit whirl and drilling failures which can increase cutter wear rate. In investigating the wear of PDC cutter, both methods show that the maximum value of horizontal force, intrinsic specific energy and stress generates high wear rate on PDC cutter.

The difference of data occurs between limestone and granite formation because the output of data of analytical method and finite element analysis is affected by the physical properties of rock formation. The best range of weight on bit and rotary speed for limestone is between 1000 N, 21.4 rpm and 4000 N, 85.6 rpm, while for granite 1000 N, 21.4 rpm and 3000 N, 64.2 rpm. At these ranges, the wear rates generated were small.

The output of the data is produced from single PDC cutter simulations. Therefore, execution of cutter test and simulation with rotary PDC cutter and for whole PDC bit are recommended in future in order to get more accurate data.

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