EFFECT OF SIZE AND GEOMETRY OF POLYCRYSTALLINE DIAMOND CUTTER (PCD) ON WEAR RATE IN MULTILAYER FORMATION

[1]Ahmad Majdi Abd Rani, [1]Kong Kai Vern, [2]Azri Hamim Ab Adzis, [1]TVVLN Rao
[1]Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia
[2]UniKL ICOLE, Universiti Kuala Lumpur, 1016, Jalan Sultan Ismail, 50250 Kuala Lumpur
For Correspondence; [2]azri@unikl.edu.my

ABSTRACT: *During a normal drilling operation, the rate of penetration (ROP) is considered more important compared with the wear rate of cutters. However, when drilling in multi-layer formations, the wear rate is a more important as it leads to more drilling time rather than focusing solely on the ROP. The project is to investigate the effect of Polycrystalline Diamond (PCD) cutter design features on the cutter wear rate in two different rock formations: one is the soft sandstone formation and other is the harder dolomite formation. The bit design features studied in the project is the shape of the cutters and the size of the cutters. The effect of drilling fluid is assumed to be optimum. Using ABAQUS, models with different shape of cutter and size of cutter are simulated against the two formations. Results are analyzed and compared to study the effects on wear and select the best model which has minimum wear rate. Result showed that 16 mm size cutter and cone shape cutter are best design to minimize the cutter wear compared to other size and geometrical shape of cutter used in the project. The 16 mm size cutter experienced 36.8% less stress compared with the 8 mm cutter and the cone shape cutter experienced 6.35% less wear compared with flat shape cutter.*

1. INTRODUCTION

Drilling is an important operation in oil and gas industry. Polycrystalline Diamond Compact (PDC) bit is used often on the drilling process.

PDC bit is a type of bit which consists of multiple Polycrystalline Diamond (PCD) cutters attached to the bit body and cut through rocks by shearing action between the cutters and the rock. The time taken for the drilling operation is directly proportional to the cost [1]. By increasing the rate of penetration (ROP) drilling time can be shortened hence reducing cost but it will also reduce the lifespan of the drill bit. Drill bit will suffer severe damage if the bit design is not suitable for the formation being drilled. Thus, the drill bit becomes another major cost of the operation as the bit needed to be taken out and replaced. The project focused on the effect of cutter design features on the wear rate, namely the cutter size and cutter shape. By minimizing the wear rate, it increases the run length of the drilling operation and directly affects the time needed for the operation, resulting in the decrease in cost and optimizes the performances.

Different PDC bit cutter designs were studied to find out which design have the minimum wear rate. The study was done using analytical model and simulation model using the ABAQUS software. The result of the analysis is used to determine the best size and shape for the cutter to minimize the cutter wear in multi-layer formations.

Bit Wear

During the drilling operation, the drill bit is subjected to highly abrasive rock and high velocity drilling fluid which will cause serious wear and corrosion to the bit profile [2]. Thus, selecting a suitable bit design that is suitable for the job is very crucial.

Abrasive wear occurred during the impact between the bit and the rock in the formation [3]. During the impact, the cutter's diamond grain is crushed against the rock, causing it to be gradually removed from the cutter. When this happened, new diamond grain is exposed to the rock and the crushing and removing process repeat itself as the drilling operation continue. Abrasive wear in soft formation is minimal, however, when the formation is layered with hard rocks, or when the hardness of the formation increased, the wear rate become more and more severe [4].The higher the difference between the bit's cutter capability and the formation hardness will cause a more severe wear rate to the bit [5].Thermal effect can also increase the wear on PDC bit as the operating temperature increase, unfavorable stress condition begins to occur in the bit. Glowka and Stone stated that the hardness of the PDC bit decreases more than 65% when the temperature rise to 1300 Fahrenheit, when compared to its hardness at room temperature. This further increase the abrasive wear of the bit [6].

Multi-layer Formation

Multi-layer formation is defined as different types of formation interbedded with another types of formation. In multi-layer formation, the hardness of the formation is always changing from soft to hard formation due to the different properties of rocks. Drilling operation in multi-layer formation often takes many bit changes as worn out drill bit has undesirable drilling performance [7]. Changing new drill bit uses up a lot of time and this increase the cost of the operation.

Cutter Design Parameters

The shape of the cutter included standard shape, curve shape and cone shape design. Different shape of the cutter will have a different effect in the removal of cuttings [8]. One of the aims of this study is to identify which shape of cutter have higher wear rate. As for cutter size, generally larger cuttings are produced when using larger cutters. Thus, improving the cleaning in soft formations. It is also believed that certain formations respond more favorably to width of cut compared to depth of cut. Smaller cutters provide long bit life in medium-soft to medium hardness formations. Mid-range cutters respond to a midpoint between the softest and hardest PDC drillable formations.

Wear Model

Merchant's cutting model is based on the principle of minimum energy. A shear of material and a friction between a tool and a chip are the two phenomena responsible for the cutting force where it was distributed on the shear force or the friction force. The effects of stress distribution and failure criteria on loading force variations are being emphasized. The stress on the tool rake face can be obtained using the equation (1) and (2) [9]:

$$\sigma = \frac{F_N}{A_N} \quad (1)$$

Where A_N is the normal contact area.

$$\tau = \frac{F_H}{A_S} \quad (2)$$

Where A_S is the shear contact area

A wear model which indicates that the total tribological system to determines the wear behavior is proposed where von Mises stress is related to wear by calculating the wear volume per unit distance, W in μm^2 using equation (3) [10, 11]:

$$W = k_2 V \bar{\sigma}^{\frac{1}{bn'}} \quad (3)$$

where k_2 is an arbitrary wear constant, V is the deformed volume, $\bar{\sigma}$ is the von Mises stress in MPa, b is a constant whose value is approximately 0.5, and n' is the cyclic strain-hardening coefficient with the value of 0.31. The typical value of $\frac{1}{bn'}$ is around 6.45 [10]. The large value of this coefficient points out that the von Mises stress in the stressed volume is dominant in the wear process and will significantly response to the wear value. The contact geometry, the mechanical properties of the materials, the friction and the externally applied forces vary the magnitude of the von Mises stress. The proportionality constant $k_2 \times V$ was taken as 1.5 x 10^{-11} [11]. For the system, the deformed volume, V is equal to $\pi a^2 d$, where a is the contact radius and d is the thickness of layer. Table I below shows the list of coefficient with different type of material.

Table 1: Ludwik Relationship of Different Materials (Tangena & Wijnhoven, 1988)

Material	Constant, K(N/mm^2)	Strain-hardening coefficient, n′	Power, $\frac{1}{bn'}$	Proportionality Constant, k_2V
Gold (Au)	478	0.63	3.15	3.36 x 10^{-2}
Polycrystalline Diamond (PCD)	573	0.31	6.45	1.50 x 10^{-11}
Nickel (Ni)	4889	0.55	3.64	3.45 x 10^{-7}
Copper (Cu)	530	0.44	4.55	3.72 x 10^{-6}
304 Stainless Steel	1400	0.44	4.55	4.48 x 10^{-6}

2. MATERIALS AND METHODS

The study is focused on single PDC cutter where wear of the cutters is studied using the general analytical model in term of cutter's shapes and sizes. Then, 3D simulation models the single PDC cutters were done using Finite Element Method (FEA) based on elastoplastic mechanics and rock mechanics. The 3D models are created with CATIA software and the FEA models are processed with ABAQUS software to analyze the stresses experienced by the cutter. From the results, the cutter with the least wear rate is determined as the best design.

Parameters

In order to reduce the number of variables for the study, some of the PDC cutter cutting parameters is being kept constant. Table 2 shows the constant parameters in the project.

Table 2: Constant Parameter

Polycrystalline Diamond Compact (PDC) Cutter	
Type of Cutter	Polycrystalline Diamond (PCD) bonded with tungsten carbide-cobalt (WC-Co)
Cutter Edge Chamfer	45 º (curve cutter only)
Cutter Edge Geometry	0.254 mm (0.010 in.) (curve cutter only)
Diamond Carbide Interface	Conventional
Back Rake Angle	15º
Operating Variable	
Weight on Bit (WOB)	25 000 lb
Rotation per minute (RPM)	170 RPM

Table 3 shows the mechanical properties of the PDC cutter and Tungsten insert.

Table 3: PDC cutter and Tungsten insert properties[4]

Mechanical Properties	PDC	WC-Co
Density ($kg \cdot m^{-3}$)	3510	15000
Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	543	100
Specific Heat ($J \cdot kg^{-1} \cdot K^{-1}$)	790	230
Thermal Expansion Coefficient ($10^{-6} K^{-1}$)	2.5	5.2
Young's Modulus (GPa)	890	579
Shear Modulus (GPa)	545	280
Poisson Ratio	0.07	0.22

Table 4 shows the properties for the formation.

	Sandstone	Dolomite
Density ($kg \cdot m^{-3}$)	1910	2700
UC Strength (MPa)	50	170
Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	2.5	5.1
Specific Heat ($J \cdot kg^{-1} \cdot K^{-1}$)	920	920
Thermal Expansion Coefficient ($10^{-6} K^{-1}$)	11.6	10.0
Elastic Modulus (GPa)	15	70
Yield Strength(MPa)	4	15
Poisson Ratio	0.14	0.15
Coefficient of Friction	0.51	1.00

3. DESIGN FEATURES

Figure 1 is the bit design features selected for the project for the cutter's size and the cutter's shape.

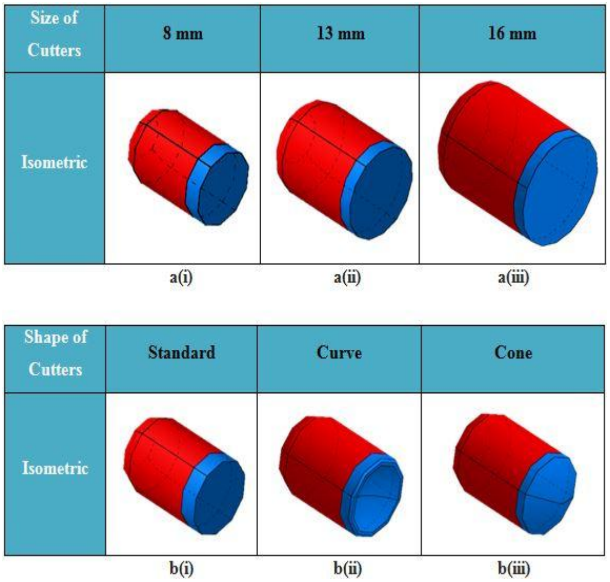

Fig. 1. a(i) 8mm bit cutter. a (ii) 13mm bit cutter. a(iii) 16mm bit cutter. b(i) standard shape cutter. b(ii) curve shape cutter. b(iii) conshape cutter

4. RESULTS AND DISCUSSION

PDC Single Cutter Analytical Model (Cutter Size)

Table 5 shows the single cutter data for different sizes.

Table 5: Single Cutter Size Data

Size of Cutter	8mm	13mm	16mm
Shape the Cutter	Flat	Flat	Flat
Normal Force, F_N	1400 N	2300 N	2500 N
Shear Contact Area, A_S	2.51E-05	6.64E-05	1.01E-04

To compute the horizontal force, the equation (4) is used [12]:

$$F_H = F_N \left[\frac{1 - \mu \tan\alpha}{\tan\alpha + \mu}\right] \quad (4)$$

Where F_H is the horizontal force, F_N is the normal force, α is the back rake angle and μ is the coefficient of friction.

Referring to Merchant's model, the equation (2) is used to calculate the shear stress on the cutter face. Figure 2 shows the chart of shear stress against the size of cutter on sandstone and dolomite formation.

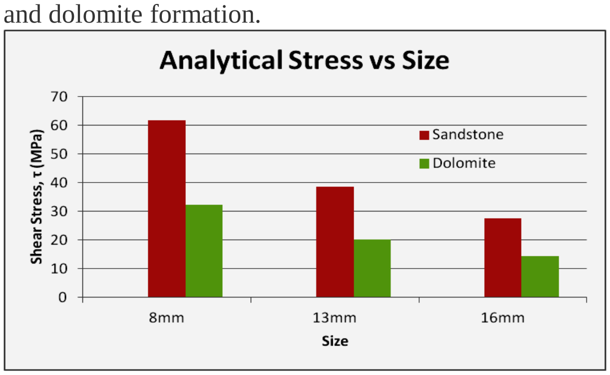

Fig. 2: Effect on Size of Cutter on Shear Stress (Analytical)

The result shows that the cutter with the size of 16mm experiences less shear stress. This is because of the decreased in the size of the cutter, which is the shear contact area of the cutter. By lowering the stress exerted on the cutter face, the cutter durability improves. Therefore, PDC cutter with the size of 16mm recommended for the formation drilling application based on the analytical model made using excel.

PDC Single Cutter Analytical Model (Cutter Shape)

Table 6 shows the single cutter data for different shapes.

Table 6: Cutter Shape

Size of Cutter	16mm	16mm	16mm
Shape of Cutter	Flat	Curved	Cone
Normal Force, F_N	2500 N	2500 N	2500 N
Shear Contact Area, A_S	1.01E-04	1.09E-04	1.40E-04

The shear contact area for different shapes of cutter is calculated using equation (2) and (4). Figure 3 shows the chart of shear stress against the shape of cutter on sandstone and dolomite formation.

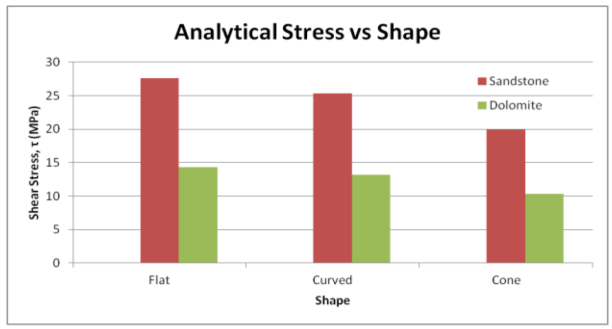

Fig 3: Effect on Shape of Cutter on Shear Stress (Analytical)

PDC Single Cutter Simulation (Cutter Size)

Figure 4 and Figure 5 below show the graph of stress against time for different size of cutter for sandstone and dolomite formations plotted from simulation results.

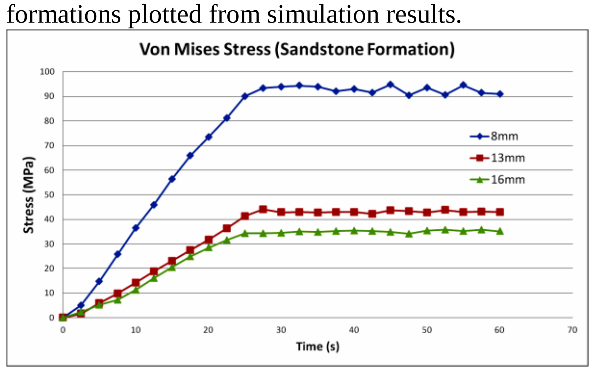

Fig 4: Graph of Stress vs Time for Different Size of Cutter (Sandstone Formation)

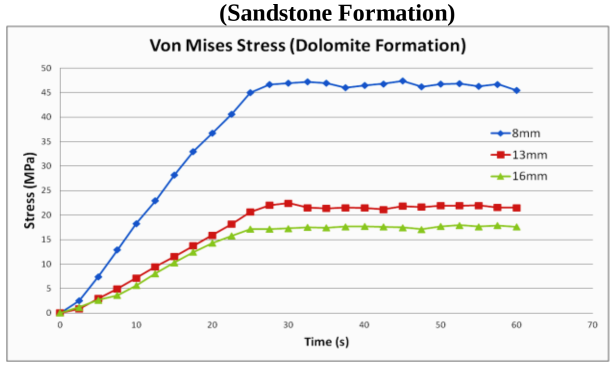

Fig. 5: Graph of Stress vs Time for Different Size of Cutter (Dolomite Formation)

The stress of the cutter climbs rapidly in the beginning and started to stable itself about 30s afterwards. This is because the simulated data is trying to reach the designated horizontal force during the beginning stage of the simulation. The average stress after it stabilizes is taken for comparison with the analytical data.

Figure 6 shows the chart of simulated shear stress against the size of cutter on sandstone and dolomite formation.

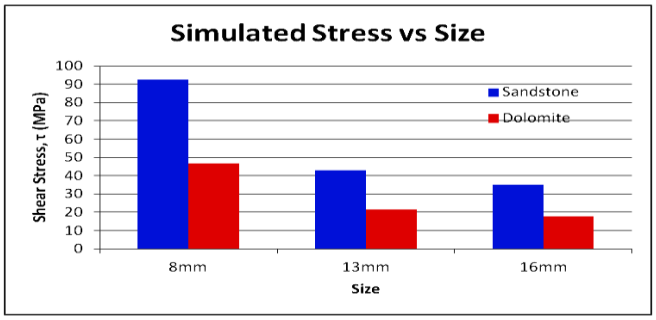

Fig. 6. Effect on Size of Cutter on Shear Stress (Simulation).

From the simulated result, the cutter with size of 16mm is best for the drilling application as it has the lowest stress compared to the other 2 sizes. This result is good, as it shows similar trends with the analytical data.

The von Mises stress obtained from the simulation data is higher than analytical data. This is due to the axial stress and not all forces are taken into the calculation of the analytical model. However, both the simulated and analytical stress data show the same behavior, which tally with the theory based on the equation. Thus, both set of data show that the best size of cutter for drilling operation in considerations of cutter durability is the cutter with 16mm size.

PDC Single Cutter Simulation Cutter's Shape

Figure 7 and Figure 8 show the graph of stress against time for different size of cutter for sandstone and dolomite formations plotted with simulation result.

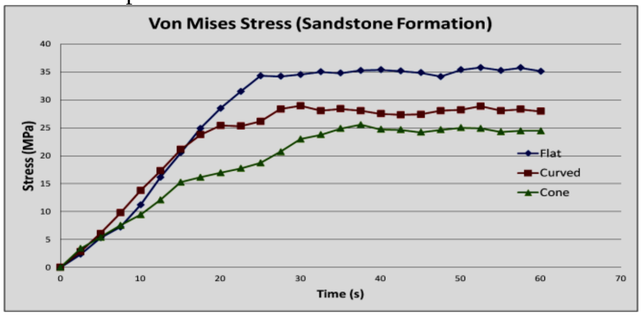

Fig. 7. Graph of Stress vs Time for Different Shape of Cutter (Sandstone Formation)

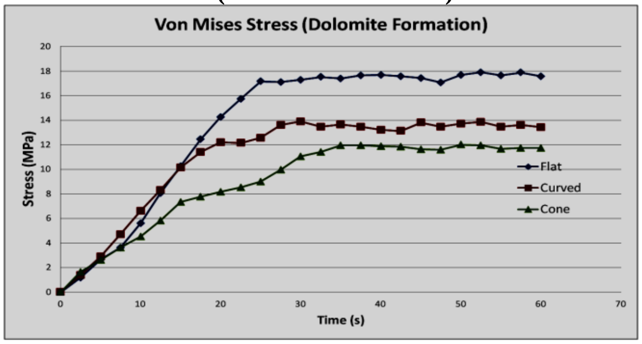

Fig. 8. Graph of Stress vs Time for Different Shape of Cutter (Dolomite Formation)

The average stress after about 30s is taken for comparison with the analytical data. Figure 9 shows the chart of simulated shear stress against the shape of cutter on sandstone and dolomite formation.

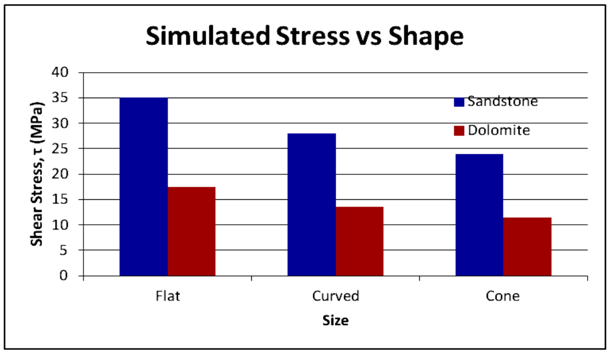

Fig. 9. Effect on Shape of Cutter on Shear Stress (Simulation)

From the simulated result, the cutter with cone shape is best for the drilling application as it has the lowest stress compared to the other 2 shapes. This is because the shear contact area of cone shape cutter is the highest and with largest shear contact area, the least stress is exerted on the cutter. The result is then validated with the comparison between the simulated data and analytical data.

The von Mises stress obtained from the simulation data is higher than analytical data. This is due to the axial stress and not all forces are taken into the calculation of the analytical model. However, both the simulated and analytical stress data show the same behaviour, which tally with the theory based on the equation. Thus, both set of data show that the best shape of cutter for drilling operation in considerations of cutter durability is the cutter with cone shape.

PDC Cutter Wear

The wear of the cutter is calculated using the equation (3) where the proportionality constant, k_2V is set at 1.5×10^{-11}, V is the deformed volume, 1/bn`is 6.45. From the equation (3), the von Mises stress is very dominant as it has a power of 6.45, while the other parameters remaining constant. The higher the stress value will result in higher wear. The magnitude of the stress is dependent on the contact geometry, the mechanical properties of the materials, the friction and the externally applied forces.

Cutter's Shape

The wear of the cutter of different shape is shown in Table 7 calculated using equation (3).

Based on the Table 7, cutter in cone shape has the least wear compared to flat and curved shape cutter. This is because cone shape cutter is with the largest shear contact area and least shear stress.

Table 7: Different Cutter Shape Wear

Shape of Cutter	Sandstone Formation		Dolomite Formation	
	Simulated Stress (MPa)	**Simulated Wear (μm^2)**	**Simulated Stress (MPa)**	**Simulated Wear (μm^2)**
Flat	3.50E+01	1.37E-01	1.75E+01	1.57E-03
Curved	2.80E+01	3.23E-02	1.35E+01	2.92E-04
Cone	2.39E+01	1.16E-02	1.14E+01	9.98E-05

5. CONCLUSION

Rate of penetration is important in optimizing the drilling performance, but by selecting suitable drill bit design, which reduces the wear rate throughout the operation and increase the run length of the drill bit is another approach too. Most of the drilling operation is occurring at multi-layer formation area which results in a more favorable choice to optimize the performance in run length rather than penetration rate. However, a maximize ROP is still favorable together with a suitable bit design for the multi-layer formation operation area. Analytical model using the combination of both cutter-rock interaction model and Merchant's cutting model is formed to study the force and stress in the PDC cutter during drilling operation. Several bit design with different size and shape of cutter are simulated in ABAQUS and the best design which produce minimum wear rate during drilling operation is obtained. Results obtained that for this project, cutter size of 16mm shows 36.8% less stress compared to 8 mm cutter. This is due to the large shear contact area which minimizes the stress and lead to less wear compared to other size of cutter. As for the shape of cutter, cone shape is the best design to minimize wear and prolong the durability. For similar size cutter, cone shape is with the largest shear contact area, which results in least wear, up to 6.35% less compared with flat shape cutter.

Due to the limitation of time and software, only simulation on the single cutter is done. The project can be improved using a better version of software and run the simulation for the whole bit instead of just on a single cutter. Further research can be made in the future to include other and more design features of the bit. Research on the other factors that would contribute to the bit wear rate can be explored too.

6. ACKNOWLEDGEMENTS

The authors would like to express a deep sense of gratitude to Y-UTP 0153AA-A66 for supporting this research.

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