Study on the Effect of Diamond Grain Size on Wear of Polycrystalline Diamond Compact Cutter

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Abstract. Drilling operation is one of the most crucial step in oil and gas industry as it proves the availability of oil and gas under the ground. Polycrystalline Diamond Compact (PDC) bit is a type of bit which is gaining popularity due to its high Rate of Penetration (ROP). However, PDC bit can easily wear off especially when drilling hard rock. The purpose of this study is to identify the relationship between the grain sizes of the diamond and wear rate of the PDC cutter using simulation-based study with FEA software (ABAQUS). The wear rates of a PDC cutter with a different diamond grain sizes were calculated from simulated cuttings of cutters against granite. The result of this study shows that the smaller the diamond grain size, the higher the wear resistivity of PDC cutter.

1. Introduction

In the Oil and Gas industry, a suitable drill bit needs to be selected to get the maximum Rate of Penetration (ROP) and to minimize the cost of drilling. The more popular types of drill bit are the Roller Cone (RC) bit and the Polycrystalline Diamond Compact (PDC) bit. PDC bit advantage over RC bit is its high ROP. RC bit, however, is more wear resistant compared with PDC.

The abrasive properties of the rock will cause the bit to be worn off and reduce its cutting efficiency. Worn PDC bit needs to be replaced with a new one. This will consume a lot of time and money. Therefore, more studies are needed to ensure PDC bit can last longer. The objective of the paper is to analyze the effect of diamond grain size of PDC cutter on wear by using Finite Element Analysis (FEA) model. The simulation models were run to get the stress distribution on the PDC cutters with various grain sizes. The stresses in the cutter then will be converted into wear rate.

2. Literature Review

2.1. Bit Wear

The definition of wear in drilling industry is when there is erosion or loss on the material surface due to the frictional force. Ekberg believed that plastic shear followed by shear fraction are signs of wear [1]. The wear of a PDC bit can be seen on the cutter. Moseley et. al. stated that common PDC cutter wear are due to bond failure between the diamond table and the bit body, chipped cutter, broken cutter, delamination, heat checking and abrasive wear [2].

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2.2. Bit Grain Size
Wilmot and Penrose claimed that the grain size of diamond gives a big impact on the abrasion and affects the resistance of a cutter. The smaller the grain size (fine particle), the higher the abrasion resistance will be. The abrasion resistance of PDC is measured in term of G-ratio. It indicates the volume of rock detached per unit diamond consumed. The greater the value of G-ratio, the greater the abrasion resistance will be [3]. The other factor which relate wear to the grain size is the amount of grain boundaries as stated by Gedeon. The grain boundaries have a function to stop the dislocation of the particles. Using smaller the grain size will lead to high ratio of surface area to volume and this will give a higher amount of grain boundaries. Thus, the strength of the material will be higher [4].

2.3. Boundary Strengthening
Material strength is strongly related to the grain size of a material. Hall-Petch equation describes the influence of the grain size on the yield strength of a material [5]. The equation describes that with smaller mean grain size, the yield strength of the material will increase and this will lead to the increase of the material strength. The Hall-Petch equation is as below.

$$\sigma_y = \sigma_o + Kd^{-0.5} \tag{1}$$

Where σ_y is the Yield Strength, σ_o is the PDC stress constant, K is the Hall-Petch constant and d is the mean grain size. The equation rationalized that the deformation caused by the dislocation motion is affected by the propagation of dislocation from a deformed grain to an un-deformed grain where the grain boundary is the wall for the dislocation to occur [6]. The dislocation will occur and pile up at the grain boundary which is the wall and will cause the stress concentration at the wall. This will lead to the deformation of a material. The number of dislocation in the pile-up affects the development of stress concentration at the boundary. However, fine-grained material has a small number of dislocation gathered at the boundary which leads to a small stress concentration at the pile up.

2.4. Analytical Model
A new 3D analytical PDC cutter-rock interaction model by taking priority of the effect of side rake angle, the coefficient friction of rock and back rake angle was developed by Rajabov, et al. and Che et al. They proved that the horizontal force acting on the cutter can be computed if the normal force, angle of the back rake and rock friction coefficient are known. They also believed that the increase of the natural force acting on the cutter will increase the horizontal force. Furthermore, they also stated that as the back-rake angle increase, the horizontal force will also increase. Below is the equation proposed by Rajabov, et al. and Che et al. [7][8].

$$F_H = F_N \left[\frac{1-\mu \tan \alpha}{\tan \alpha + \mu}\right] \tag{2}$$

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

Based on Merchant’s cutting model, the total stress acting on the cutter can be calculated. However, there are a few assumptions made in Merchant’s model by Juneja, Sekhon and Seih such as the tool must have a sharp edge, the cutting edge is a straight-line perpendicular to the direction of the cutter and it generates a place surface as the work moves past it. Furthermore, the workpiece experienced the deformation across the thin shear plane and it is rigid and perfectly plastic. Moreover, the shearing surface is a plane extending upward from the cutting edge and the chip does not flow to side. Finally, the depth of cut is kept constant between work and tool with continuous chip [9].

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The total stress acting on the bit is the summation of normal stress and shear stress or horizontal stress. The higher the contact area on the cutter, the lower the total number of stress acting on the PDC cutter is. The wear model is an analytical model that can compute a number from Von Mises stress acting on the material into the wear rate value respective to the stress acting on the material [10]. The wear model equation is:

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

Where W is the wear rate, k_2 is an arbitrary wear constant, V is the total volume deformed, σ is the Von Mises stress in MPa, b is the constant which is 5 and n' is the cyclic strain-hardening coefficient. In this model, V which is the total volume deformed is approximately equal to Pi x r^2 x d, where r is the radius of contact area and d is the thickness of the material. For PDC cutter, the value of k_2 is 573 N/mm^2, n' is 0.31, 1/bn' is 6.45 and k_2V is 1.5 x 10^{11} [11].

3. Methodology

3.1. PDC Single Cutter Test

The theoretical basis of the PDC cutter was studied using the general analytical model. A 3D simulation model of rock breaking using a single PDC cutter was established with Finite Element Method (FEA) based on elastoplastic mechanics and rock mechanics. The single cutter FEA models of various grain sizes of PDC cutter were done using ABAQUS to identify the Von Mises stress acting on the cutter and to determine the best grain size. Similar FEA set up was used by Ahmad Majdi et. al. to study the effect of cutter sizes and geometry [12].

3.2. Design Features

Based on Hall-Petch Equation, the Yield Strength of a material can be computed by changing its grain size. Table 1 shows the yield strength of cutters with different grain sizes.

Table 1. Yield Strength of PDC Cutter

Diamond Grain Size (μm)	Yield Strength (MPa)
5	5849.7
15	4286.1
25	3804.6
50	3320.0

3.3. Parameters

A single PDC cutter model was simulated to cut against a granite block. A cylindrical cutter of radius 0.012m and thickness of 0.0035m is chosen with back rake angle kept constant at 10o and the depth of cut is 0.003m. Table 2 shows the PDC cutter and granite parameters.

Table 2. Physical Properties of PDC Cutter and Granite

	PCD	Granite
Unconfined Compressive Strength, UCS (MPa)	N/A	300
Density, ρ (kgm^{-3})	3510	26200
Young's Modulus, E (GPa)	890	70
Poisson Ratio	0.07	0.30
Shear Modulus, G (GPa)	545	N/A
Ultimate Tensile Strength, UTS (MPa)	N/A	256
Shear Yield Stress, τ_{yield} (MPa)	N/A	132
Kinetic Coefficient, μ_k	0.45	0.45

Figure 1 shows the cutter and granite block configuration. There are two forces acting on the cutter which are normal force, F_N and horizontal force, F_H, where F_N is equal to the weight on bit acting on the cutter itself. The cutter is assumed to move in a straight direction with a constant velocity of 0.306 m/s. The objective of the analytical model is to identify the axial stress and shear stress acting on the PDC cutter during the drilling operation.

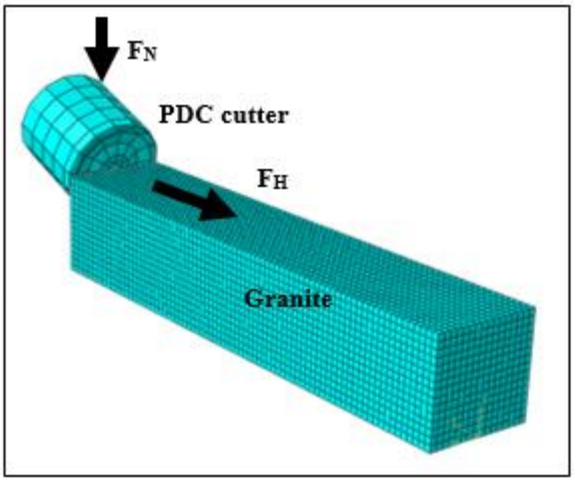

Figure 1. Single Cutter Model

4. Results and Discussion

4.1. PDC Single Cutter Analytical Model

The PDC cutter test data are shown in Table 3. From equation (1), the value of horizontal force, FH acting on the single PDC cutter is 3678.81 N. The total stress acting on the single PDC cutter can be calculated by adding up the axial stress and shear stress.

Table 3. Behaviour of PDC Cutter

Parameters	Value
Surface Area of Cutting Face, A	4.5238x10-4 m^2
Shear Contact Area, A_s	3.2640x10-5 m^2
Horizontal force	3678.81 N
Normal stress, σ	5.517 MPa
Shear stress, τ	112.5895 MPa
Total Stress	118.1065 MPa

4.2. PDC Single Cutter Simulation

A 3D model of PDC cutter and formation was designed by using ABAQUS FEA. The horizontal force and normal force are applied on the PDC cutter which were obtained from the analytical model. The boundary condition of the formation is set as "Encastre" and the PDC cutter is set as "Velocity" with x-axis velocity of 0.306 m/s. The simulation step period is set to be 1.5 step. The tabulated Von Mises stresses acting on the PDC cutter is converted in a graph and is shown in the Figure 2. The graph showed that the smaller the grain size, the lesser the Von Mises stresses acting on the PDC cutter.

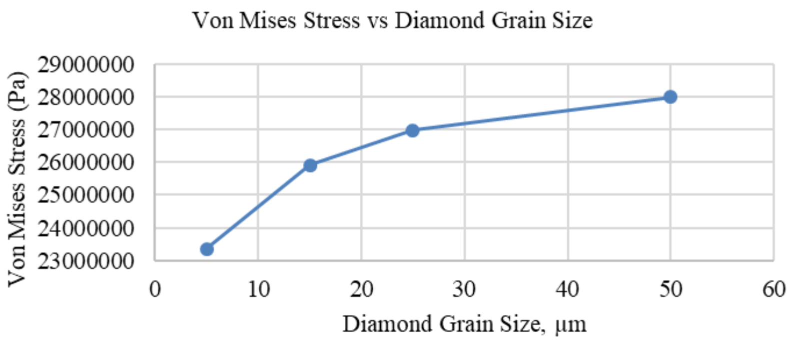

Figure 2. Von Mises Stress vs Diamond Grain Size

4.3. PDC Cutter Wear Rate

The Von Mises Stress recorded from the simulation result then can be converted into wear rate value using equation (2). The wear rate then can be analyzed to determine the best diamond grain size for material properties of PDC cutter. Based on the result shown in Figure 3, it can be concluded that the higher the Von Mises stress, the higher the wear rate of the material will be.

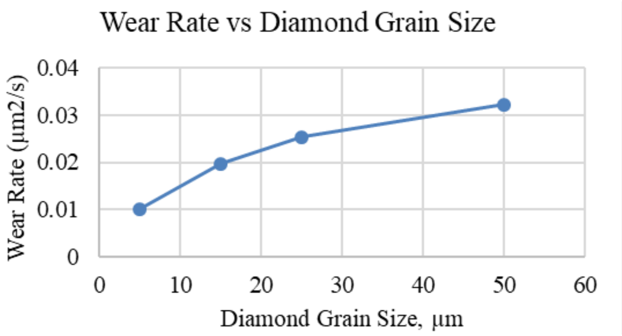

Figure 3. Wear Rate vs Diamond Grain Size

From the Figure 3, it can be observed that the wear rate decreases as the diamond grain size increases. The smaller diamond grain size will have the most grain boundary and naturally will increase the yield strength of the material which makes it more wear resistance. So, the diamond grain size should be kept small to maximize the yield strength of the cutter and maximize the cutter life.

5. Conclusion

This project shows the result of effect of diamond grain size on wear of PDC cutter through Finite Element Analysis method. An analytical model is used to compute the velocity, horizontal force and normal force to be applied in the simulation. The simulated 3D model of single PDC cutter and formation with variable diamond grain sizes. The constant parameters are the back-rake angle, the depth of cut and other material properties. The resultant Von Mises stress distribution from the simulations are converted into wear rate by using the wear model. The result shows that the smaller the diamond grain size, the lesser the stress distribution exerted on the cutter. This is due to the larger grain boundary which leads to lesser dislocation piled up at the boundary. This in turn will cause lesser stress to be exerted on the cutter. In conclusion, this project found that 5µm size of diamond grain has the best properties to reduce cutter wear rate.

6. Recommendation

It is recommended to simulate the model using a longer range of period step. The longer period step will give a better result because the once the time taken reach the optimum time, the stress distribution number will keep constant and stable.

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