Numerical simulation of rock cutting using 2D AUTODYN

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Abstract. In a drilling process for oil and gas exploration, understanding of the interaction between the cutting tool and the rock is important for optimization of the drilling process using polycrystalline diamond compact (PDC) cutters. In this study the finite element method in ANSYS AUTODYN-2D is used to simulate the dynamics of cutter rock interaction, rock failure, and fragmentation. A two-dimensional single PDC cutter and rock model were used to simulate the orthogonal cutting process and to investigate the effect of different parameters such as depth of cut, and back rake angle on two types of rocks (sandstone and limestone). In the simulation, the cutting tool was dragged against stationary rock at predetermined linear velocity and the depth of cut (1, 2, and 3 mm) and the back rake angles (-10$^\circ$, 0$^\circ$, and +10$^\circ$) were varied. The simulation result shows that the +10$^\circ$ back rake angle results in higher rate of penetration (ROP). Increasing depth of cut leads to higher ROP at the cost of higher cutting force.

1. Introduction

Due to depletion of hydrocarbon reserves at shallow depth, oil and gas industries attempt to drill for reserves at a greater depth. Exploration and production wells are drilled to produce these hydrocarbons. Unfortunately, it is difficult to exactly predict the interaction between the cutting tool and rock before the drilling operation. Understanding the interaction between the cutting tool and the rock is important to optimize the drilling process through higher rate of penetration (ROP) and better tool life [1, 2]. There are three types of drill bits used in oil and gas industry, namely: roller cone bits, fixed cutter bits and hybrid bits. The selection and use of these bits depend on several factors such as formation to be drilled, projected operating parameters, the capabilities of rig and the operator’s past experience in offset wells. In this paper, PDC (Polycrystalline Diamond Compact) bit, which falls under fixed cutter category and one of most commonly used cutting tool in industry, is considered to assess the effect of different parameters on the drilling operation.

Experimental investigation of rock cutter interaction can help to understand the effects of different parameters. However, the high cost of conducting such experiments, the difficulty to exactly represent the downhole conditions in the experimental setup, time to conduct a number of experiments, and difficulty to directly observe the rock fragmentation and removal process leads to numerical simulation as a means to study the process at early stage. There are a number of factors which affect the performance of PDC bit with respect to ROP. Some of these parameters include weight on bit (WOB), depth of cut, rpm of the bit, rock hardness and bit design features. The bit design features include cutter material, number of cutters, cutting structure geometry (back rake angle and side rake angle), and other features.
The effect of back rake angle and side rake angle were studied by Gerbaud, Menand [2] (to estimate the cutting force. Rajabov, Miska [3] studied the effect of back rake angle and side rake angle on the mechanical specific energy (MSE) and aggressiveness of PDC cutters. Hareland, Nygaard [4] identified back rake angle, depth of cut and rock properties to be factors affecting the cutting efficiency using single PDC cutter. A variety of simulation codes and models have been used in the literature to study cutter-rock interaction. ANSYS AUTODYN has been used by [5, 6] to simulate the tunnel boring machine (TBM) and evaluate the cutter efficiency. LS-DYNA has been used by [1, 7] to study rock fragmentation. Some of the researchers [8-10] used discrete element simulation for rock-cutter interaction.

In this study, a two-dimensional code ANSYS AUTODYN-2D is used to simulate the cutter-rock interaction, rock failure, fragmentation and study the effect of different parameters such as depth of cut, and back rake angle on two types of rocks namely sandstone and limestone. ANSYS AUTODYN [11] is an explicit analysis tool for modeling nonlinear dynamics of solids, fluids, gas, and their interaction. AUTODYN-2D is capable of simulating non-linear, dynamic fracture failure and fragmentation.

2. Numerical method

Numerical simulations were performed using an explicit non-linear finite element code AUTODYN-2D. Material models in AUTODYN consist of equation of state (EOS), strength model and failure model. Material models can either be selected from available models in the library or defined by the user. In this section, the numerical models for the cutter and rock block together with the boundary conditions imposed for different sets of simulation will be described.

2.1. Modeling the cutter

The PDC bits are designed and manufactured either as matrix body bits or steel body bits. Their selection depends on the application. Matrix body PDC bits, which are made from composite materials consisting of tungsten carbide grains bonded with metallic binder, are abrasion and erosion resistant compared to steel body bits. On the other hand, steel body bits are preferred for their strength and high resistance in impact loading. In this paper diamond impregnated bit with matrix body construction is considered. The cutter material is considered to be Tungsten, the properties of which are available in AUTODYN library. In selecting the cutter material the deformation of the cutting tool is negligible compared to the rock, and the wear or abrasion of the cutter is insignificant. Thus, no failure mode was defined for the cutter and it is assumed to be rigid.

2.2. Modeling the rock

Two types of rock materials were considered in this study. The properties of the rocks are presented in table 1. As this rock models are not available in the material library of AUTODYN, new material models were defined. The rock models were assumed to be isotropic and homogenous. The rock models are defined with linear EOS. For strength model, the Drucker-Prager model is adopted. The Drucker-Prager model is used to represent the behavior of the rocks where the cohesion and compaction behavior result in an increasing resistance to shear up to a limiting value of yield strength as the loading increases. The model requires the compressive and tensile strengths of the rock. The yield point under uniaxial compression and tension were assumed to be 90% of the uniaxial compressive and Brazilian tensile strength [6]. For failure model, principal stress failure which is used to represent brittle failure in materials was used. The failure stress was defined by the Brazilian tensile strength.
Table 1. Properties of rock materials.

| Rock Type | Density, $\rho$ (Kg/m$^3$) | Uniaxial compressive strength, $S_c$ (MPa) | Brazilian tensile strength, $S_T$ (MPa) | Young’s modulus, $E$ (GPa) | Poisson’s ratio, $\nu$ | Bulk modulus, $B$ (GPa) | Shear modulus, $s$ (GPa) |
|-----------|-----------------|----------------------|----------------------|----------------------|------------------|-----------------|-----------------|
| Sandstone | 2000            | 170                  | 15                    | 15                   | 0.14             | 6.94            | 6.58            |
| Limestone | 2700            | 210                  | 25                    | 30                   | 0.28             | 22.73           | 11.72           |

2.3. Model set-up and boundary conditions

During drilling operation, the PDC cutter is dragged in a circular path due to the rotation of the bit. Figure 1(a) shows the sketch of a single cutter in a vertical plane together with the rock model and parameters. The cutter is tilted with an angle, $\phi$ (back rake angle) with respect to the rock and the side rake angle is assumed to be zero. An arbitrary relief angle ($\alpha$) is used.

The cutter and rock models were virtually represented in AUTODYN as shown in figure 1(b). The rock was modeled as a rectangular block of 20 mm in length and 40 mm in height. The cutting tool is modeled as square element with side length of 10 mm. The top nodes of the rock were fully constrained in X- and Y-directions and the sides are constrained in the X-direction while the bottom side is free. The cutting tool was constrained in the Y-direction. The back rake angle of the cutting tool, $\phi$, was varied between $+10^\circ$, $0^\circ$, and $-10^\circ$. The cutting tool was dragged against stationary rock at linear velocity of 100 mm/s. The sliding contact between the cutter tip and the rock was assumed to be frictionless. The depth of cut, $dc$, was varied between 1, 2, and 3 mm during simulation. A gauge was defined at the tip of the cutter to measure the different parameters such as force, pressure, stresses and strains during the cutting process. The interaction between the cutter and the rock is defined with small external gap before the simulation starts.

Figure 1. (a) Schematic representation of PDC cutter in a vertical plane with cutting parameters and (b) Cutter and rock model with $+10^\circ$ back rake angle.

3. Result and discussion

3.1. Fragmentation

The erosion option in AUTODYN is used to analyze the total mass of the debris after the cutting process. When the failure criterion is reached, the rock element will fail and remove from the rock block in the form of chip. Figure 2(a) shows the reduction in total mass due to failure for sandstone
with 3 mm depth of cut and $0^\circ$ rake angle for the entire cutting process along the length. Figure 2(b) shows a comparison of total mass removed for different rake angles and depth of cuts. The $+10^\circ$ rake angle has the highest rock mass reduction while $0^\circ$ has the least. Based on this simulation $+10^\circ$ rake angle is recommended to get higher ROP. This is in good agreement with the result by [12] where the mean cutting force was reported to be the least at $+15^\circ$ rake angle compared with $0^\circ$ and $-15^\circ$. Furthermore, the total mass reduction increases with increasing depth of cut which leads to higher ROP.

**Figure 2.** (a) Total mass of sandstone for $0^\circ$ rake angle with 3 mm depth of cut and (b) Variation of total mass removed with depth of cut and rake angle.

Fragmentation option in AUTODYN was used to study rock fragments in terms of size and mass. The fragment plot only shows elements that contained material that has not failed. The fragment analysis at 1500 cycles for all simulation is as shown in figure 3. In all cases, sandstone has higher number of fragments and total mass compared to limestone. In addition, the number and mass of fragments increase with depth of cut.

**Figure 3.** Variation of total mass of small fragments with depth of cut at 1500 cycles.
3.2. Cutting Force

The chip formation in the rock is due to shearing and crushing when the cutting tool moves against stationary rock. This phenomenon has been observed in the force vs cutting distance history as shown in figure 4 with a number of peaks and valleys. The peaks indicate the higher resistance from the rock followed by chip formation due to shearing and drop in force magnitude. The crushing mechanism is depicted with small variation in the force with relatively small magnitude in the valleys. Similar observations have been reported by Che et al. [13] using experimental data and simulation results from LS-DYNA. The cutting force increases with depth of cut for both sandstone and limestone. In all simulations, a higher magnitude of cutting force is observed when cutting limestone compared with sandstone which agree with the observation by [12].

![Figure 4](image1.png)

**Figure 4.** Horizontal cutting force with 3 mm depth of cut and $+10^\circ$ rake angle (a) sandstone and (b) limestone.

![Figure 5](image2.png)

**Figure 5.** Variation of cutter velocity with depth of cut and rake angle.

The velocity profile of the cutter depicts similar trend with the cutting force. When there is higher resistance, the speed of the cutter decreases until the cutter force reaches peak value followed by chip formation due to shearing mechanism. This results in weaker rock with lower internal energy, hence the speed of the cutter increase again. This fluctuation in resistance and force leads to lower overall velocity of the cutter compared to the initial velocity. The variations in the final velocity of the cutter with depth of cut and rake angle is shown in figure 5. The velocity decreases with depth of cut which...
indicate higher cutting force as well. Similarly, limestone has higher velocity reduction which requires higher cutting force.

4. Conclusion
In this paper, it was attempted to simulate the cutting tool rock interaction for single cutter PDC bit. The effect of depth of cut and back rake angle on fragmentation, chip formation, and cutting force has been analyzed. These effects have been simulated for two types of rocks: sandstone and limestone. Based on this simulation +10º rake angle is recommended to get higher ROP with least mean cutting force. Furthermore, increasing depth of cut leads to higher ROP at the cost of higher cutting force. Future work includes three dimensional analysis and construction of experimental test rig to validate the simulation results.

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