Investigating the effects of PDC cutters geometry on ROP using the Taguchi technique

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Abstract. At times, the polycrystalline diamond compact (PDC) bit’s performance dropped and affects the rate of penetration (ROP). The objective of this project is to investigate the effect of PDC cutter geometry and optimize them. An intensive study in cutter geometry would further enhance the ROP performance. The relatively extended analysis was carried out and four significant geometry factors have been identified that directly improved the ROP. Cutter size, back rake angle, side rake angle and chamfer angle are the stated geometry factors. An appropriate optimization technique that effectively controls all influential geometry factors during cutters manufacturing is introduced and adopted in this project. By adopting L₉ Taguchi OA, simulation experiment is conducted by using explicit dynamics finite element analysis. Through a structure Taguchi analysis, ANOVA confirms that the most significant geometry to improve ROP is cutter size (99.16% percentage contribution). The optimized cutter is expected to drill with high ROP that can reduce the rig time, which in its turn, may reduce the total drilling cost.

1. Introduction

PDC cutters have gained popularity in petroleum drilling due to its durability together with its ability to maintain a high ROP. Nevertheless, due to abrasive wear, impact and abrasive damage, the extension of the cutters application into hard rock drilling has been the greatest challenges that faced by today manufacturer. A lot of studies have been conducted for a better understanding of cutters geometry with an intention to enhance drilling performance. Designed cutters with higher ROP efficiency and longer cutter's life are quite often the objective. There is a various investigation conducted discussing the influence of cutter geometry towards the drilling performance. Knowlton [1] proposed a modified geometry of cutter with positive rake angle which overcame the difficulties encountered in drilling shale formations. While, in another study, Gerbaud et al. [2] adding more complexities to cutter geometry and incorporating the chamfer made on some cutters in their established model for better drilling efficiencies. Generally speaking, cutters optimization refers to designing a cutter with the highest ROP efficiency and longest drilling. Thus, in order to minimize the critical condition during drilling, optimization technique was quite often applied to simplify the manufacturer’s work in determining the optimal design features during their manufacturing process. Taguchi technique is known as one of best and effective optimization techniques [3].

Developed by Dr. Genichi Taguchi, the Taguchi technique [4] is widely applied to optimize the manufacturing process through the design parameters setting. In order to plan a good framework and deciding the ideal controllable parameter settings, which are invulnerable to noise, the Taguchi technique has the solution [5]. Taguchi technique presents an integrated approach that is very straightforward in order to find the best range of design parameters for the best performance and
quality [6]. The (1) parameter design, (2) system design and (3) tolerance design are the most three common phases adapted in this technique [7]. Out of all the three, parameter design is recognized as the most vital for process optimization [8]. Orthogonal Array (OA), signal-to-noise (S/N) ratios, and ANOVA are the special features that have been introduced in Taguchi technique. Taguchi OA is a fractional orthogonal design used to appraise the main effects by running only a few experiments. As a consequence, using OA can decrease the costs and at the same time examining a huge number of parameters rather than studying one parameter at a time as done in conventional techniques [9]. The Taguchi concept was further discussed by Roy [10].

The primary objective of this paper is to study the impacts of cutter geometry on the ROP. By incorporating with L₀ Taguchi OA, the explicit dynamics finite element analysis (FEA) were run to obtain the ROP results. Using the S/N ratio and ANOVA, the optimal geometry factors or levels and the impacts of cutter geometry on ROP performance are further evaluated.

2. Methodology

For the finite element analysis, a single cutter with the dimension of 8mm, 13mm and 16mm diameter, 8mm height and 2mm diamond table thickness is used as a model and is shown in Figure 1. In this study, the ROP is simulated by using ANSYS explicit dynamic finite element analysis model. The initial conditions file consist of a pre-stress object to control the exchange of information from an implicit static or transient structural analysis to the explicit dynamics analysis. Transferable data consists of the displacements or a complete material state while the analysis settings incorporate boundary condition, body interaction and erosion are defined under explicit dynamics.

With 300 rpm, the angular velocity is defined as the initial condition. Other parameters like the formation fixed support, the bit constant angular velocity and the bit force are embedded under analysis settings. In the real situation, weight on bit is the weight of the drill pipe up to the surface. This weight acting as a force to push the bit into the rock formation. In this simulation, the value of weight on bit was set as 100,000 Newton.

2.1. Geometrical factors and simulation

The objective of this work is to find out the influences of geometry factors on drilling performance. ROP is chosen as the quality objective to be considered. Based on the previous study, four geometries are selected to be run in FEA simulation. Table 1 shows the geometry factors and level values. L₀ (3⁴) OA is chosen as the experimental layout for simulation runs. Table 2 presented the L₀ OA.

| Column | Factors          | Level 1 | Level 2 | Level 3 |
|--------|------------------|---------|---------|---------|
| A      | Cutter size (mm) | 8       | 13      | 16      |
| B      | Back rake angle  | 0       | 5       | 25      |
| C      | Side rake angle  | 0       | 15      | 30      |
| D      | Chamfer angle    | 15      | 30      | 45      |
The simulation run shows the number of conducted simulations (Table 2). Nine simulation runs are conducted in this study and allocated as trial 1 to trial 9. Factor A to factor D represent the geometry factors: A for cutter size, B for back rake angle, C for side rake angle and D for chamfer size (Table 1). Each factor is allocated to column 1 to column 4. While, the ROP is recorded in the last column. The simulations are run as displayed in Table 2. In Trial 1, the simulation is conducted by a set of geometry factors consist of cutter size (A) at 8mm, back rake angle (B) at 0°, side rake angle (C) of 0° and chamfer angle (D) of 15° respectively.

### 3. Analysis method

#### 3.1. Signal-to-noise (S/N) ratio

In order to identify the quality of the output, Taguchi presented the utilization of signal-to-noise (S/N) ratio. The S/N ratio is a measurement of performance focusing on developing processes and products that invulnerable to uncontrollable factors [11]. Depending on the quality characteristic, there are differences of S/N available that can be categorized to smaller-the-better, nominal-the-best and higher-the-better where each type of them are represented by different formula calculation and depend on experiment objective [12]. The larger value of S/N ratio indicates the robustness of the product against the noise and this principle is similarly applicable for all three smaller-the-better, nominal-the-best and higher-the-better characteristics [13]. In this study, the equation higher-the-better can be used for analysis of ROP properties. In this study, the equation for “higher-the-better”, as shown in equation (1) can be used for analysis of ROP.

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S/N = -10 \log_{10} \left[ \frac{y_1^2 + y_2^2 + y_3^2 + \cdots + y_n^2}{n} \right] \tag{1}
\]

where the value of the quality characteristics is denoted as \( y \) and the number of repetitions is denoted as \( n \).

### 4. Results and discussion

The following steps were conducted to decide the optimal cutter geometry: (1) S/N ratios for the simulation results were computed, (2) Main effect graph was evaluated (3) Geometry factor analysis of variance (ANOVA) were calculated.

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**Table 2. L_9 OA used in simulation.**

| Run No. | A Cutter size (mm) | B Back rake angle (°) | C Side rake angle (°) | D Chamfer angle (°) | ROP (m/hr) |
|---------|--------------------|-----------------------|----------------------|---------------------|------------|
| 1       | 8                  | 0                     | 0                    | 15                  | 85.62      |
| 2       | 8                  | 5                     | 15                   | 30                  | 75.60      |
| 3       | 8                  | 25                    | 30                   | 45                  | 68.32      |
| 4       | 13                 | 0                     | 15                   | 45                  | 11.24      |
| 5       | 13                 | 5                     | 30                   | 15                  | 11.78      |
| 6       | 13                 | 25                    | 0                    | 30                  | 11.21      |
| 7       | 16                 | 0                     | 30                   | 30                  | 10.36      |
| 8       | 16                 | 5                     | 0                    | 45                  | 8.54       |
| 9       | 16                 | 25                    | 15                   | 15                  | 8.75       |
4.1. S/N ratio computation
In this study, the simulation results of ROP performance for all nine runs are analyzed by using S/N ratios based on the larger-the-better quality characteristic (Equation 1). Table 3 summarized the S/N ratios for all nine runs.

| Run No. | ROP (dB) |
|---------|----------|
| 1       | 38.65    |
| 2       | 37.57    |
| 3       | 36.10    |
| 4       | 21.02    |
| 5       | 21.42    |
| 6       | 20.99    |
| 7       | 20.31    |
| 8       | 18.63    |
| 9       | 18.84    |

4.2. Main effect analysis
The main effects for each factor are calculated from the S/N ratio results shown in Table 3. Through the main effect graph, the changes in ROP due to the variations in cutter geometry can be analyzed. The optimal sets of geometry factors and levels can be predicted further. Figure 2 shows the main effects of Taguchi technique.

Basically, the larger value of S/N ratio will produce the better ROP performance. Referring to Figure 2, A₁, B₁, C₁, and D₂ show the largest value of the S/N ratio for geometries A, B, C, and D respectively. As a result, the optimal geometry which statistically results in the maximum ROP are predicted to be the cutter size of 8mm, back rake angle of 0°, side rake angle of 0° and chamfer angle of 30°.

4.3. Analysis of variance (ANOVA)
Analysis of variance (ANOVA) was conducted on the S/N ratio results (Table 3) to investigate the influence of individual factor on ROP performance. Table 4 present the degrees of freedom (DOF), the sum of square (S), variance (V), and the percentage contribution (P).
Table 4. ANOVA for ROP S/N ratio.

| Column | Factors       | DOF | S    | V    | P (%) |
|--------|---------------|-----|------|------|-------|
| A      | Cutter size  | 2   | 599.64 | 299.82 | 99.16 |
| B      | Back rake angle | 2   | 2.76  | 1.38  | 0.46  |
| C      | Side rake angle | 2   | 0.12  | 0.06  | 0.02  |
| D      | Chamfer angle | 2   | 2.19  | 10.95 | 0.36  |
|        | Other/error   | 0   | 0     | 0     | 0     |
|        | Total         | 8   | 604.71| 0     | 100   |

Referring to Table 4, as a level of confidence of 95% is used in this study, the significance of the geometry factors to the ROP was cutter size, back rake angle, side rake angle and chamfer angle accordingly. The most decisive factor will be given the maximum value of the percentage of contribution for each geometry. As shown in Table 4, it can be observed that the cutter size is the most influential geometry which demonstrates the highest P of 99.16%. The analysis revealed that the size had the strongest correlation to the ROP performance in cutter operation and in this case the predicted optimum melt temperature for the part is 8mm.

5. Conclusion
The optimal geometry conditions of PDC cutter geometry were investigated by using the Taguchi technique. The ability of the Taguchi’s technique to improve the ROP in response with a few numbers of runs with an acceptable accuracy level has been determined. The findings demonstrated that the Taguchi technique can maximize the ROP and can, along this line, be applied in future studies for an assortment fields. In addition, the contribution of each geometry to ROP was also decided by using the procedure explained. Through a series of analysis and optimization, the outcomes displayed that the optimal cutter geometry to results in maximum ROP was decided as A1, B1, C1, and D2. The cutter size demonstrates the strongest influence among the four vital geometries investigated in this study followed by back rake angle, chamfer size and side rake angle. The information gained in this work should help engineers to make better decisions in maximizing the ROP.

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