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Research paper

Optimizing wear rate for PDC cutter using taguchi’s technique and response surface methodology a comparative analysis

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Abstract

This paper presents the findings of a simulation results on the effects of chamfer angle, back rake angle, side rake angle and diame-ter on polycrystalline diamond compact (PDC) cutter wear rate. Design of experiment techniques, i.e. Taguchi’s technique and re-sponse surface methodology (RSM), have been used to accomplish the objective of the study. L9 orthogonal array and face centered central composite (fc-CCD) design have been used for conducting the experiments. Taguchi’s technique as well as 3D surface plots of RSM revealed that chamfer angle is the most significant factor in minimizing wear followed by back rake angle and side rake angle. The effects of cutter diameter were found to be insignificant compared to other factors. Though both the techniques predict-ed near similar results, RSM technique seems to have an edge over the Taguchi’s technique.

Keywords: *Cutter; Geometry; Wear Rate; Taguchi; Response Surface Methodology.*

1. Introduction

Polycrystalline diamond compact (PDC) cutter have gained popularity in drilling for petroleum due to its high endurance together with its ability to maintain a high rate of penetration (ROP). One of the greatest challenges that any cutter manufacturer faces today is the extension of PDC its application into hard rock drilling, where impact damage, heat damage and abrasive wear limits performance. Research and development have been focused on better understanding of cutters geometry with an intention to enhance drilling performance.

Higher ROP efficiency and longer life is almost always the objective during PDC cutter manufacturing. There is a number of published studies discussing the effect of cutter geometry on performance of drilling operation. Knowlton [1] proposed a modified orientation of cutter with positive rake angle which overcame the difficulties encountered in drilling shale formations. While, in other 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, cutter geometry optimization refers designing a PDC cutter with the highest ROP efficiency and longest drilling life for given formation properties

In any experimental or simulation studies investigations, statistical design of experiments is used quite extensively. Statistical design of experiments refers to the process of planning the experiment so that the appropriate data can be analyzed by statistical methods, resulting in valid and objective conclusions [3]. DOE methods such as factorial design, response surface methodology and Taguchi methods are now widely used in place of one-factor-at-a-time experimental approach which is time consuming and exorbitant in cost.

The objective of this experimental investigation is to ascertain the effects of chamfer angle, back rake angle, side rake angle and cutter diameter on wear rate of PDC cutter. Design of experiment techniques, i.e. Taguchi’s technique and response surface methodology (RSM), have been used to accomplish the objective. L9 orthogonal array and face centered central composite design have been used for running the simulations.

2. Design of experiment techniques – a brief review

2.1. Taguchi’s technique

Taguchi’s parameter design is an important tool for robust design. It offers a simple and systematic approach to optimize design for performance, quality and cost. Two major tools used in robust design are signal to noise ratio, which measures quality with emphasis on variation, and orthogonal array, which accommodates many design factors simultaneously [4-6]. Taguchi’s design is a fractional factorial matrix that ensures a balanced comparison of levels of any factor. In this design analysis each factor is evaluated independent of all other factors.

Taguchi has built upon W.E. Deming’s observation that 85% of poor quality is attributable to the manufacturing process and only 15% to the worker. When a critical quality characteristic deviates from the target value, it causes a loss [5]. Continuously pursuing variability reduction from the target value in critical quality characteristics is the key to achieve high quality and reduce cost. By applying this

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technique one can significantly reduce the time required for experimental investigation, as it is effective in investigating the effects of multiple factors on performance as well as to study the influence of individual factors to determine which factor has more influence and which has less [7-12].

2.2. Taguchi's technique

RSM is a collection of mathematical and statistical techniques that are useful for modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [3]. RSM also quantifies relationships among one or more measured responses and the vital input factors. The version 6 of the Design-Expert Software was used to develop the experimental plan for RSM [13]. The same software was also used to analyze the data collected. A regression is performed on the data collected wherein the observed variable (response) is approximated based on a functional relationship between the estimated variable and one or more input variables. The least square technique is used to fit a model equation containing the said input variables by minimizing the residual error measured by the sum of square deviations between the actual and the estimated responses. This involves the calculation of estimates for the regression coefficients, i.e. the coefficients of the model variables including the intercept or constant terms. However, the calculated coefficients of the model equation need to be tested for statistical significance. In this respect, three tests are performed—test for significance of the regression model, test for significance on individual model coefficients and test for lack-of-fit [14].

Additionally, checks need to be made in order to determine whether the model actually describes the experimental data [14]. The checks performed here include determining the various coefficients of determination (R2). These R2 coefficients have values between 0 and 1. In addition to this, the adequacy of the model is also investigated by the examination of residuals [3]. The residuals are the differences between the observed and the predicted responses and these are examined using the normal probability plots of the residuals and the plots of the residuals versus the predicted response. If the model is adequate, the points on the normal probability plots of the residuals should form a straight line. On the other hand, the plots of the residuals versus the predicted response should be structure less, that is, they should contain no obvious patterns.

3. Simulation details

3.1. Work specimen

For the finite element analysis, a single PDC cutter compliance to International Association of Drilling Contractors (IADC) with diameters of Ø = 13mm, 16mm and 19mm diameter, 8mm height and 2mm diamond table thickness is used as a model and is shown in Figure 1.

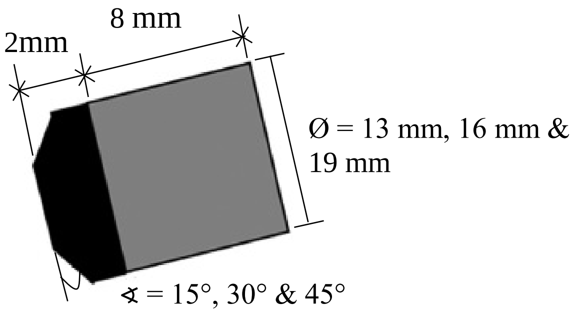

Fig. 1: Geometry and Dimension of PDC Cutter.

3.2. Simulation

In this study, the wear is simulated by using ANSYS explicit dynamic finite element analysis model. The Initial Conditions folder includes a Pre-Stress object to control the transfer of data from an implicit static or transient structural analysis to the explicit dynamics analysis. Transferable data include the displacements or the more complete Material State (displacements, velocities, stresses, strains, and temperature) while the Analysis Settings include erosion, boundary condition and body interaction are defined under explicit dynamics.

Angular velocity of 300 rpm is defined as initial condition. Other parameters such as force on top of the PDC bit, the constant angular velocity of PDC bit and fixed support of rock formation are inserted under analysis settings. In the real drilling situation, weight on bit (WOB) is the weight of the drill pipe up to the surface. This weight acting as a force to push the PDC bit into the rock formation. In this drilling simulation, the author defined the value of WOB as 100,000 Newton.

3.3. Taguchi's experimental design - L9 orthogonal array

As per Taguchi's method the total DOF of the selected OA must be greater than or equal to the total DOF required for the experiment. So, an L9 (37) OA (a standard three-level orthogonal array) having 14 DOF was selected for the present work. The non-linear relationship among the geometry parameters, if it exists, can only be revealed if more than two levels of the parameters are considered [15]. Thus each selected parameter was analyzed at three levels. The geometry parameters and their values at three levels are given in Table 1.

Table 1: Font Specifications for A4 Papers

Column	Parameters	Level 1	Level 2	Level 3
A	Chamfer angle (°)	15	30	45
B	Back rake angle (°)	0	5	25
C	Side rake angle (°)	0	15	30
D	Chamfer angle (°)	15	30	45

Wear rate being a 'lower the better' type of cutter quality characteristic, the S/N ratio for this type of response was used and is given below:

$$S/N = -10\log_{10}(y_1^2 + y_2^2 + y_3^2 + \cdots y_n^2)/n \tag{1}$$

Where y_1, y_2,…y_n are the responses of the wear characteristic, for a trial condition repeated n times. The S/N ratios were computed using (1) for each of the 9 trials and the values are reported in Table 2.

Table 2: Experimental Data of Wear Rate for Taguchi Technique

Run	A	B	C	D	Results
	Chamfer angle (°)	Back rake angle (°)	Side rake angle (°)	Chamfer angle (°)	S/N ratio (dB)
1	15	0	0	15	30.12
2	15	5	15	30	30.10
3	15	25	30	45	31.24
4	30	0	15	45	28.93
5	30	5	30	15	29.98
6	30	25	0	30	29.96
7	45	0	30	30	30.24
8	45	5	0	15	30.07
9	45	25	15	15	30.20

3.4. RSM experimental design – central composite design (CCD)

The drilling process was studied with a standard RSM design called a central composite design (CCD) wherein the factorial portion is a full factorial design with all factors at three levels, the star points are at the face of the cube portion on the design which correspond to α-value of 1. This is commonly referred to as a face centered CCD. The center points, as implied by the name, are points with all levels set to coded level 0, the midpoint of each factor range. Thirty experiments were performed. The design layout is as shown in Table 3.

Table 3: Experimental Data of Wear Rate for RSM Technique

Run No.	A	B	C	D	Results
	Chamfer angle (°)	Back rake angle (°)	Side rake angle (°)	Cutter diameter (mm)	Wear rate (x10-9 mm3.N-1.m-1)
1	15	0	0	15	86
2	45	0	0	15	112
3	15	25	0	15	92
4	45	25	0	15	138
5	15	0	30	15	114
6	45	0	30	15	152
7	15	25	30	15	118
8	45	25	30	15	168
9	15	0	0	45	88
10	45	0	0	45	118
11	15	25	0	45	98
12	45	25	0	45	140
13	15	0	30	45	116
14	45	0	30	45	164
15	15	25	30	45	128
16	45	25	30	45	180
17	15	12.5	15	30	112
18	45	12.5	15	30	148
19	30	0	15	30	116
20	30	25	15	30	132
21	30	12.5	0	30	106
22	30	12.5	30	30	134
23	30	12.5	15	15	126
24	30	12.5	15	45	126
25	30	12.5	15	30	128
26	30	12.5	15	30	128
27	30	12.5	15	30	124
28	30	12.5	15	30	126
29	30	12.5	15	30	126
30	30	12.5	15	30	126

4. Analysis and discussion

4.1. Taguchi's technique

Using the S/N ratio data in Table 2, the average performance or main effects for each factor are computed. The changes in wear rate due to the variations in PDC cutter's geometry can be evaluated through the main effect graph, and the optimal sets of geometry/levels can be predicted further. The main effects analysis of the Taguchi's technique are plotted in Figure 2.

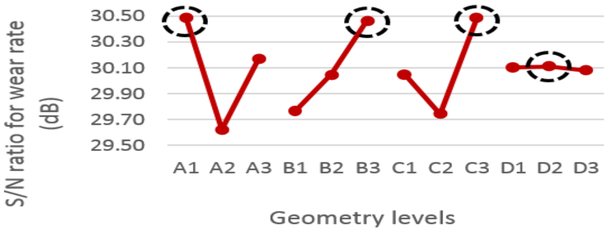

Fig. 2: Main Effect Plot for Cutter Wear Rate.

Basically, the larger the S/N ratio value, the better are the endurance of the cutter. In this case, the comparability sequence with a larger value of S/N ratio will result in small volume of wear rate. Referring to Figure 2, A1, B3, C3, and D2 show the largest value of S/N ratio for designs A, B, C, and D respectively. As a result, the optimal cutter geometry which statistically result in the reduction of wear rate are predicted to be the chamfer angle of 15°, back rake angle of 25°, side rake angle of 30° and cutter diameter of 30mm.

In order to quantify the influence of cutter geometry on wear characteristic, analysis of variance (ANOVA) is performed on the S/N ratio value for nine comparability sequences (Table 2). The computed quantity of degrees of freedom (DOF), sum of square (S), variance (V), and percentage contribution (P) is presented in Table 4.

Table 4: S/N ANOVA

Column	Parameters	DOF	SS	V	P (%)
A	Chamfer angle	2	33.80	16.90	88.92
B	Back rake angle	2	2.28	1.14	5.99
C	Side rake angle	2	1.88	0.94	4.95
D	Cutter diameter	2	0.05	0.025	0.13
	Other/error	0	0	0	0
	Total	8	38.01		100

Referring to Table 4, as a level of confidence of 95% is used in this study, the significance of the cutter geometry to the wear rate was chamfer angle, back rake angle, side rake angle and cutter diameter accordingly. The most decisive factor will be given the maximum value of percentage of contribution for each geometry. As shown in Table 4, it can be observed that the chamfer angle is the most influential design which demonstrates the highest P of 88.92%. The analysis revealed that the chamfer angle had the strongest correlation to the wear characteristic in PDC cutter operation and in this case the predicted optimum chamfer angle is 15°. The influence of cutter diameter was found to be insignificant which demonstrates P is less than 1% of contribution to wear.

4.2. RSM technique

The results from the simulation trials performed as per the experimental plan are shown in Table 3. Without performing any transformation on the response, these results were input into the Design-Expert Software for further analysis. Test for significance of the regression model, test for significance on individual model coefficients and test for lack-of-fit need to be performed. An ANOVA table (Table 5) is commonly used to summarize the tests performed. The value of “P > F” for models is less than 0.05, which indicates that the model is significant which is desirable as it indicates that the terms in the model have a significant effect on the response. The value of $P < 0.0001$ indicates that there is only a 0.01% chance that a “model F-value” this large could occur due to noise. Values greater than 0.1000 indicate the model terms are not significant. Some of the model terms were found to be significant. A, B, C, D, AB and AC, are significant model terms The insignificant model terms can be removed and may result in an improved model.

Table 5: ANOVA for Response Surface Model

Source	DOF	SS	V	F-value	p-value Prob > F
Model	14	13815.56	986.83	87.53	< 0.0001
A	1	7523.56	7523.56	667.33	< 0.0001
B	1	4867.56	4867.56	431.75	< 0.0001
C	1	910.22	910.22	80.74	< 0.0001
D	1	150.22	150.22	13.32	0.0024
AB	1	144.00	144.00	12.77	0.0028
AC	1	121.00	121.00	10.73	0.0051
AD	1	9.00	9.00	0.80	0.3857
BC	1	16.00	16.00	1.42	0.2520
BD	1	4.00	4.00	0.35	0.5603
CD	1	25.00	25.00	2.22	0.1572
ABC	1	16.00	16.00	1.42	0.2520
ABD	1	16.00	16.00	1.42	0.2520
ACD	1	9.00	9.00	0.80	0.3857
BCD	1	4.00	4.00	0.35	0.5603
Residual	15	169.11	11.27		
Lack-of-fit	10	157.78	15.78	6.96	0.0224
Pure error	5	11.33	2.27		
Cor. total	29	13984.67			
Std. dev.	3.36		R-Squared		0.9879
Mean	125.67		Adj. R-Squared		0.9766
CV (%)	2.16		Pred. R-Squared		0.9591
PRESS	572.64		Adeq. Precision		38.866

The lack-of-fit was also found to be insignificant. Insignificance of lack-off it signifies that it is not significant relative to the pure error. This is desirable, as we want a model that fits. By selecting the backward elimination procedure to automatically reduce the terms that are not significant, the resulting ANOVA tables for the reduced model for wear rate are shown in Tables 6. Results show that the models are still significant. However, the main effect of chamfer angle was found to be the most significant factor followed by back rake angle, side rake angle and cutter diameter. Besides, the two-level interaction were also found to be significant model terms. The lack-of-fit can still be said to be insignificant. The R2 value is high, close to 1, which is desirable. The predicted R2 is in reasonable agreement with the adjusted R2. The adjusted R2 value is particularly useful when comparing models with different number of terms.

Table 6: ANOVA for Reduced Response Surface Model

Source	DOF	SS	V	F-value	p-value Prob > F
Model	6	13716.56	2286.09	196.11	< 0.0001
A	1	7523.56	7523.56	645.41	< 0.0001
B	1	4867.56	4867.56	417.56	< 0.0001
C	1	910.22	910.22	78.08	< 0.0001
D	1	150.22	150.22	12.89	0.0015
AB	1	144.00	144.00	12.35	0.0019
AC	1	121.00	121.00	10.38	0.0038
Residual	23	268.11	11.66		
Lack-of-fit	18	256.78	14.27	6.29	0.0256
Pure error	5	11.33	2.27		
Cor. total	29	13984.67			
Std. dev.	3.41		R-Squared		0.9808
Mean	125.67		Adj. R-Squared		0.9758
CV (%)	2.72		Pred. R-Squared		0.9666
PRESS	467.39		Adeq. Precision		58.861

Adequate precision compares the range of the predicted values at the design points to the average prediction error. Ratios greater than 4 indicate adequate model discrimination. Table 6 show the value was well above 4. The following equations are the final empirical models for cutter wear rate.

$$Wear\ rate = 16.85 - 0.08A - 32.59B + 272.22C + 7.22D + 0.50AB + 3.44AC \tag{2}$$

The desirability value of 1 corresponds to lowest value of wear rate in the given range of parameters as given in Table 1. Ramp function graph are given in Figure 3. Ramp function graphs shows what shall be the value of parameters to obtain lowest value of wear rate.

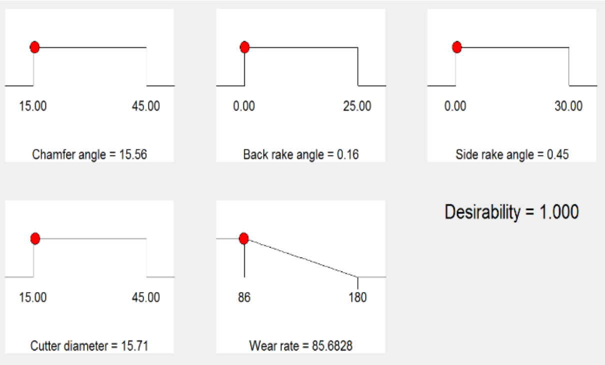

Fig. 3: Ramp Function Graph for Cutter Wear.

The model has a curvilinear profile. From the 3D surface plots it is clear that higher desirability value is at lowest level of chamfer angle, back rake angle, side rake angle and cutter diameter (Figure 4 to 6).

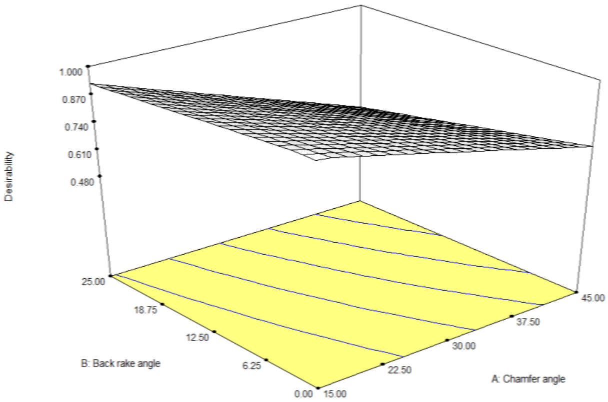

Fig. 4: 3D Surface Graph for Back Rake Angle and Chamfer Angle.

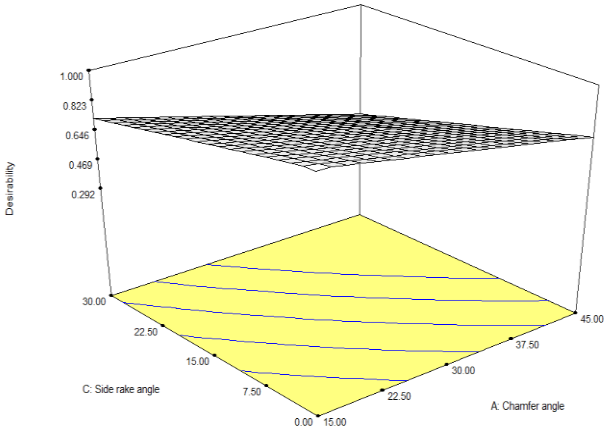

Fig. 5: 3D Surface Graph for Side Rake Angle and Chamfer Angle.

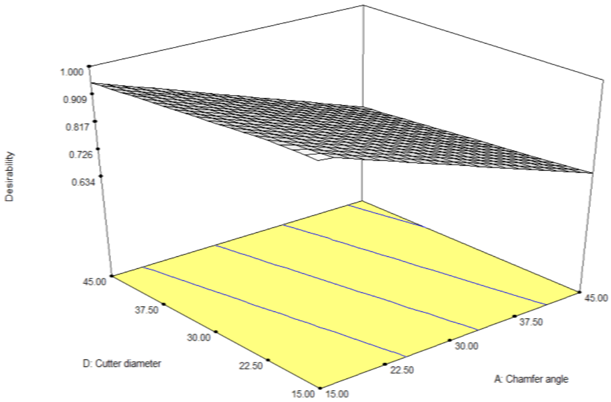

Fig. 6: 3D Surface Graph for Cutter Diameter and Chamfer Angle.

5. Confirmation test

5.1. Taguchi's technique

A confirmation test was performed at predicted level of the parameters, i.e. lowest level of chamfer angle, highest level of back rake angle, highest level of side rake angle and middle level of cutter diameter (A1B3C3D2). The wear rate was 116x10-9 mm3.N-1.m-1 which falls between the predicted intervals.

5.2. RSM technique

In order to verify the adequacy of the model developed, five confirmation experiments were performed. The test conditions are among the cutting conditions that were taken previously. Using the point prediction capability of the software, the wear rate of the selected simulations was predicted together within the 95% prediction interval. The predicted values and the associated prediction interval are based on the model developed previously. The predicted value and the actual simulated value were compared and the percentage error calculated. These values are presented in Table 7.

Table 7: Confirmation Experiment

Chamfer angle (°)	Back rake angle (°)	Side rake angle (°)	Cutter diameter (mm)	Actual wear rate (x10^{-9} mm^3.N^{-1}.m^{-1})	Predicted wear rate (x10^{-9} mm^3.N^{-1}.m^{-1})	Error
45	0	30	15	152	152.03	-0.02
45	25	0	45	140	144.46	-3.19
45	12.5	15	30	148	148.24	-0.16
30	12.5	15	45	126	129.98	-3.16
30	12.5	15	30	126	127.09	-0.87

The percentage error range between the actual and predicted value for wear rate is −3.19 to -0.02%. It can be said that the empirical models developed were reasonably accurate. All the actual values for the confirmation run are within the 95% prediction interval. The 95% prediction interval is the range in which we can expect any individual value to fall into 95% of the time.

6. Conclusion

1) The analysis of the results for cutter wear rate shows that the techniques, Taguchi and RSM methodology, give similar results. Taguchi's technique revealed that chamfer angle is the most significant factor followed by back rake angle and side rake angle. The 3D surface plots of RSM also revealed that chamfer angle has very significant effect in reducing cutter wear rate. The lowest value of wear rate in the given range of parameters as depicted by ramp function graphs are 85.6828x10-9 mm3.N-1.m-1.

2) Significance of interactions terms of parameters is more clearly predicted in RSM. The RSM shows significance of all possible combinations of interactions terms as depicted in Tables 6. Interaction of parameters are analyzed in RSM whereas none of them is done in Taguchi's technique. This is owing to the fact that in Taguchi's design, interactions between control factors are aliased with their main effects.
3) Time required for conducting simulations using RSM technique was almost triple as that needed through Taguchi technique. It is attributed to the fact that 30 were performed using face centered central composite design whereas only 9 simulations were performed using L9 orthogonal array.
4) As evident from (1), RSM technique can model the response in terms of significant parameters and their interactions. This facility is not provided by Taguchi's technique.3D surfaces generated by RSM (Figs. 4–6) can help in visualizing the effect of cutter geometry on wear rate in the entire range specified whereas Taguchi's technique gives the average value of response at given level of parameters. Also ramp function graphs tell the exact level of parameters for desired level of response. Thus, RSM can better predict the effect of parameters on response and is a better tool for optimization.

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