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TAGUCHI OPTIMIZATION AND EXPERIMENTAL INVESTIGATION OF THE PENETRATION RATE OF COMPACT POLYCRYSTALLINE DIAMOND DRILLING BITS IN CALCAREOUS ROCKS

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ABSTRACT

In the field of drilling there is increasing interest in topics such as degradation of drilling tools and estimation of penetration speed, as well as efforts to optimize geometrical parameters and drilling processes. The current study was based on an original experimental setup that estimates the actual operating conditions of drilling tools and proposed mathematical models with and without interactions. These models characterize the penetration speed of a widely used compact polycrystalline diamond (PDC) oil-drilling bit. The special focus of this study was on the cutter penetration bit, with the aim of investigating the influence of four operating variables weight on bit (WOB), bit rotational speed (RPM), cutting angle β, and compressive strength Cs on yield maximum penetration rate, using Taguchi's design-of-experiment concepts. In the study, 27 experimental runs based on Taguchi's L_{27} orthogonal array were performed with signal to-noise (S/N) ratio, analysis of variance (ANOVA), and regression analysis being used, with penetration rate as response variables. From the optimization and experimental analyses conducted, it was observed that WOB_3 (160 kgf), RPM_3 (152 rpm), β_3 (45°), and Cs_1 (640 kgf/cm^2) had significant influence on penetration rate. The optimal values obtained during the study optimization using the Taguchi approach were validated by confirmation experiments.

Keywords: ANOVA analysis; Drilling bit; Penetration rate; Signal-to-noise; Taguchi

1. INTRODUCTION

Drilling plays a vital role in oil and gas exploration and production around the world. Drilling efficiency is linked to the additional costs involved in using a platform, which can reach several hundreds of thousands of dollars a day (Wang et al., 2012). One of the most important parameters in planning drilling operations and the estimation of cost is the penetration rate (ROP) (Bilgin et al., 2003), this depending on operational variables including controllable parameters, such as operational variables, bit type, diameter, weight, and rotational speed, as well as rock properties and geological conditions (Moeni et al., 2014).

Drill-bit design is one of the factors that affects ROP during drilling (Gerbaud et al., 2011), and so the drilling industry and research community carry out continuous research into drill-bit design to improve overall drilling performance and reduce drilling costs and thus to increase margins. The choice of bit depends on several factors, one of which is whether the formation to be drilled is hard, soft, medium hard or medium soft (Moeni et al., 2014).

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A PDC bit is a drilling tool that uses polycrystalline diamond compact cutters to shear rock formations using a continuous scraping motion. The introduction of PDC in 1973 facilitated the development of the first drill bit that used synthetic diamonds as cutting elements (Kerr et al., 1988). Through continuous research and development over the last decade, PDC drill-bit performance has been improved by innovation in PDC wear, impact resistance, and better understanding of vibration. According to Kerr et al. (1988), there are three main design features affecting PDC drill-bit performance: the number of blades with cutters, cutter edge geometry and the diameter of cutters. In planning an efficient drilling operation, it is essential to learn how all these parameters influence the penetration rate.

In 1960, Taguchi proposed an effective statistical technique based on experimental data (Antony, 2006) and designed to involve tolerance and parameters in design (Taguchi, 1987; Taguchi, 1993). In contrast to previous experimental techniques, Taguchi's developed technique takes into consideration the effects of several factors. To enhance response quality by using only a few experimental data, the Taguchi method has been used to design an orthogonal array which includes S/N ratio, noise, and controlled factors (Phadke, 1989; Ross, 1996; Fotis et al., 2008; Venkateswarlu et al., 2010; Celik, 2010). Up until now, this method has been used for drilling-parameter optimization with considerable success (Changheon et al., 2017; Derdour et al., 2017; Rais et al., 2017; Derdour et al., 2018).

This experimental study was carried out by applying Taguchi methodology to provide complete information on all factors impacting on the performance parameters, such as cutting angle, WOB, rotation speed and compressive strength. From these experiments, it is possible to determine the drilling parameters that give a maximum penetration rate.

2. EXPERIMENTAL DETAILS

2.1. Laboratory Investigation

2.1.1. Tools and equipment

In this investigation, three types of sedimentary (limestone and marble) rocks were collected from different localities in Algeria reflecting variety of hardness. During sample collection, each block was inspected for macroscopic defects, to ensure use of test specimens free of fractures. Penetration rate of drill-bit setup was carried out for the three different rock samples. The blocks were approximately 30 cm × 30 cm × 4 cm in size.

Figure 1 Rock A from the quarry of ENOF unit, El Ghedir

Figure 2 Rock B from the quarry of Hadjar Soud

Figure 3 Rock C from the Felfla quarry

In this study, the experiments were carried out using a specially designed vertical drill rig to measure ROP in a simulation of the rotary drilling process. The drill bits used were PDC cylinder cutters in which cutting angle was varied between 3°,8° and 45°. During drilling, ROP was measured for different sedimentary rocks at different WOBs and RPMs.

Table 1 Properties of the drilling bit rig

Drilling Properties	
Maximum power output of the motor	1.5 kw
Maximum bit weight	250 kgf
Maximum rotary speed	220 rpm
Bit diameter	13 mm

Figure 4 Experimental drilling rig

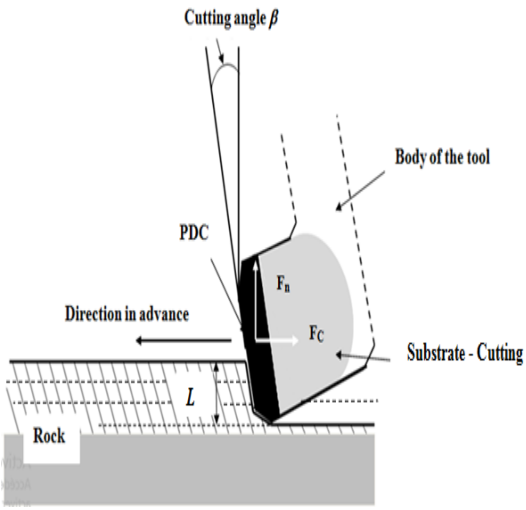

Figure 5 Construction of a PDC cutter

2.2. Determination of Rock Properties

Compressive strength is determined by placing a sample on the table of a hydraulic press, then applying a charge until total crushing of the sample is achieved. Resistance is then calculated using the following formula (Khochemane, 1990):

$$Cs = \frac{F}{S}; kgf/cm^2 \quad (1)$$

Table 2 Compressive strength of the rocks

Rocks	Compressive strength
Rock A	1550 kgf/cm^2
Rock B	750 kgf/cm^2
Rock C	640 kgf/cm^2

2.3. Plan of Investigation

In this study, the drilling experiments are planned based on Taguchi experimental design. A Taguchi L_{27} orthogonal array is used to discover the influence of various control parameters, such as cutting angle (β), WOB, RPM, and compressive strength (Cs) on penetration rate developed during drilling. In this study, three levels and three factors are considered, as presented in Table 3.

Table 3 Factors and levels selected

Factors	Unit	Code	Levels		
			1	2	3
Cutting angle	Degree	β	3	8	45
Weight on bit	kgf	WOB	80	120	160
Rotation speed	rpm	RPM	118	135	152
Compressive strength	kgf/cm^2	Cs	640	750	1550

3. METHOD OF ANALYSIS

3.1. Taguchi Technique

Taguchi developed a special design of orthogonal arrays that can be used to study the entire parameter space with only a small number of experiments. A statistical scale called signal-to-noise (S/N) ratio was used to analyze the test results, because this ratio represents both the mean and the variation (dispersion) of the experimental results in this method. The underlying principle is to use basic data obtained from experiments together with knowledge, in the form of orthogonal matrices of the S/N ratios in dB, to represent and evaluate a response to a quality or a characteristic, with the largest S/N ratio being the required response (Celik, 2010; Periyanan et al., 2011; Kang & Hadfield, 2015). There are three categories used in S/N ratio analysis techniques, namely smaller-the-better, nominal-the-best, and larger-the-better. Larger-the-better is used where a higher value is desired, as shown by Equation 2:

Larger-the-better is used where a higher value is desired:

$$S/N\ ratio(\eta) = -10\log_{10}\frac{1}{n}\sum_{i-1}^{n}\frac{1}{y_i^2} \quad (2)$$

Smaller-the-better is used where a lower value is desired:

$$S/N\ ratio(\eta) = -10\log_{10}\frac{1}{n}\sum_{i-1}^{n}y_i^2 \quad (3)$$

Nominal-the-best is used where a minimum value is desired:

$$S/N\ ratio(\eta) = -10\log_{10}\frac{1}{n}\frac{\mu^2}{\sigma^2} \quad (4)$$

where i = 1, 2,…n, μ is mean, σ is variance and y_i is the response value for an experimental condition (Vellaiyan et al, 2018).

The S/N ratio for each level of the process parameters was calculated based on S/N analysis. Regardless of the quality characteristic category, the highest results among the S/N ratios correspond to a better-quality characteristic and therefore the optimal level for process parameters is the level with the highest S/N ratio (Periyanan et al., 2011; Shafee et al., 2014).

3.2. Experimental Plan

The design of the experiment is an important factor in carrying out the tests using the available means. The Taguchi table was chosen because of the minimum number of experimental tests needed; it is more efficient when using many variable factors than full factorial designs (Taguchi, 1993) or fractional factorial designs. In addition, L_{27} was chosen to increase the accuracy of the test, is shown in Table 4.

The experimental matrix is composed of four columns, corresponding to the selected factors, and 27 lines, representing the series of rotary drilling experiments carried out. In the last two columns, the experimental values of the penetration rate and their calculated S/N ratios are reported. The signal noise of the penetration rate is calculated with the Equation 2 to maximize the penetration rate, while the penetration rate is determined by the Equation 5 (Derdour et al., 2017):

$$ROP = L/t_d\ ;mm/s \quad (5)$$

where L is the depth of the drill bit and t_d is the time taken in the drilling process, identified to eight seconds in these experiments.

Table 4 Taguchi's L27 orthogonal array

Tests	β	WOB	RPM	Cs	ROP	(S/N)	Tests	β	WOB	RPM	Cs	Pr	(S/N)
1	3	80	118	640	0.71	-2.9748	15	8	120	152	640	2.53	8.0624
2	3	80	135	750	0.95	-0.4455	16	8	160	118	1550	1.17	1.3637
3	3	80	152	1550	0.28	-11.0568	17	8	160	135	640	2.82	9.0050
4	3	120	118	750	1.01	0.0864	18	8	160	152	750	2.91	9.2779
5	3	120	135	1550	0.49	-6.1961	19	45	80	118	640	0.96	-0.3546
6	3	120	152	640	2.01	6.0639	20	45	80	135	750	1.60	4.0824
7	3	160	118	1550	1.48	3.4052	21	45	80	152	1550	1.13	1.0616
8	3	160	135	640	2.02	6.1070	22	45	120	118	750	1.43	3.1067
9	3	160	152	750	1.92	5.6660	23	45	120	135	1550	1.71	4.6599
10	8	80	118	640	1.32	2.4115	24	45	120	152	640	3.02	9.6001
11	8	80	135	750	1.43	3.1067	25	45	160	118	1550	1.61	4.1365
12	8	80	152	1550	0.80	-1.9382	26	45	160	135	640	3.01	9.5713
13	8	120	118	750	1.29	2.2118	27	45	160	152	750	3.34	10.4749
14	8	120	135	1550	1.49	3.4637							

4. RESULTS AND DISCUSSION

4.1. Analysis of S/N Ratio

Figure 6 shows the effects of the source factors on the mean values of the penetration rate, any increases in the drilling operational parameters, and the geometric parameters of the drill bits (WOB, RPM, and β, respectively) that should lead in principle to increased penetration rate. In contrast, any increase of Cs causes deceleration of the penetration rate.

Table 5 Responses for S/N ratios based on larger-is-better assumption

Level	β	WOB	RPM	Cs
1	0.07282	-0.67865	1.48805	5.27688
2	4.10717	3.45100	3.70606	4.17415
3	5.14877	6.55640	4.13465	-0.12227
Delta	5.07596	7.23505	2.64659	5.39915
Rank	3	1	4	2

The optimum levels of the means of S/N ratios of the ROP values at all factors and levels are given in Table 5. The highest S/N ratio specified for each factor provides the best experimental result, namely the experimental result with the maximum penetration rate. The average S/N ratios corresponding to each level of control factors for penetration rate are given in Figure 6.

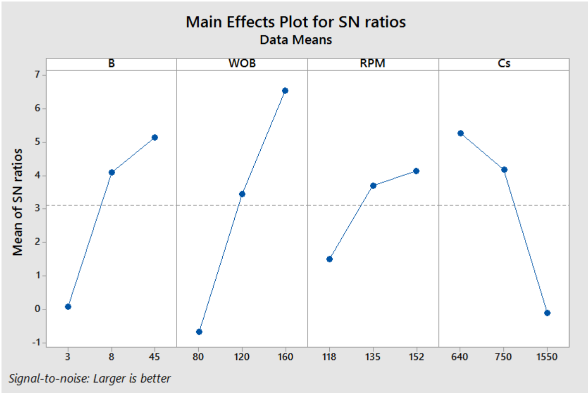

Figure 6 Main factor effects plot for S/N ratios on penetration rate (ROP)

Figure 7 Main factor effects for means on penetration rate (ROP)

In Figure 6, the highest S/N ratios demonstrate a significant impact of the parameter on the penetration rate. Under these experimental conditions, the results obtained (see Table 5 and Figure 7) show that the effects of WOB and Cs on the penetration rate are greater than those of RPM and β.

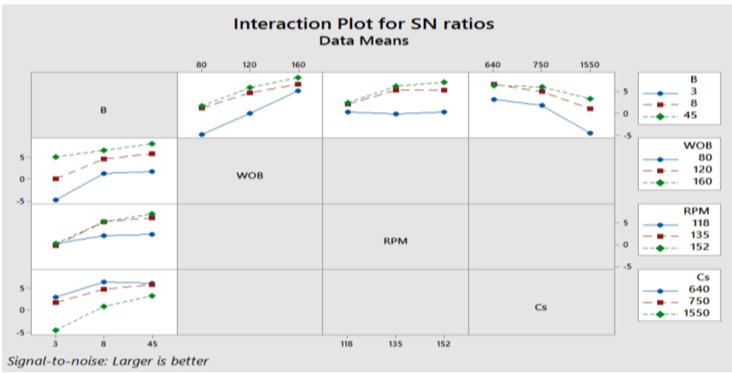

Figure 8 Interaction plots for penetration rate for all factors

Figure 8 shows the interaction for S/N ratios between the source factors and their effects on the penetration rate. These optimum control factors for obtaining a maximum penetration rate involve the following combination of experimental factors: $\beta_3WOB_3RPM_3Cs_1$, where $\beta_3 = 45°$; $WOB_3 = 160$ kgf; $RPM_3 = 152$ rpm; and $Cs_1 = 640$ kgf /cm^2, as presented in Table 6.

Table 6 Optimal parameters for the drilling bit

Factor (level)	β_3	WOB_3	Rpm_3	Cs_1
Value	45	160	152	640
S/N	5.14877	6.55640	4.13465	5.27688
Rank	3	1	4	2

4.2. ANOVA Pareto Analysis

Statistical analysis of the obtained results was performed using the ANOVA Pareto method, due to its simplicity and effectiveness. It is also quick to use and does not need to be tested by the Fisher method (Derdour et al., 2017). ANOVA Pareto analysis enables determination of the percentage of the most important parameters and also confirms information on prevalence and effect, appropriate here because the most important parameters in this experiment were already known. In the current work, the ANOVA Pareto method has been used with the S/N ratio in order to simplify the obtained results and summarize them, as presented in Table 7. Sum of the squares of the differences (S) for each factor are also shown (Hamdan et al., 2012). Table 7 shows the initial statistical analysis using the ANOVA Pareto method.

Table 7 Analysis of variance (ANOVA Pareto) of drilling

Level	β	WOB	RPM	Cs
1	0.07282	-0.67865	1.48805	5.27688
2	4.10717	3.45100	3.70606	4.17415
3	5.14877	6.55640	4.13465	-0.12227
Sum of squares of differences (S)	43.126	79.0434	12.1075	48.826
Contribution ratio (%)	23.552	43.168	6.612	26.665
Rank	3	1	4	2
Cumulative contribution ratio	93.385	43.168	100	69.833

4.3. Development of Mathematical Model

A quadratic regression model was developed for penetration rate (ROP) based on experimental results using MINITAB software, Version 16. The model helped to predict the response as a function of independent variables and their interactions. A second-order response surface model equation is as follows:

$$Y = b_0 + \sum_{i=1}^{n} b_i x_{iu} + \sum_{i}^{n} b_{ii} x_{iu}^2 + \sum_{\substack{i=1 \\ i \prec j}}^{n} b_{ij} x_{iu} x_{ju} + \varepsilon \tag{6}$$

In the mathematical model (Equation 6), Y represents the response x_{iu} while x_{ju} are the input parameters (factors), b_0 is the constant of the regression equation, b_i are the linear coefficients, b_{ii} are the quadratic coefficients, b_{ij} are the interaction coefficients, and ε is the fitting error (Montgomery et al., 2001; Wang et al., 2007; Tetteh et al., 2018).

The coefficients of the model for the corresponding response are estimated using the regression analysis technique for level of significance $\alpha = 5\%$, and level of confidence of 95%.

The expected final model for the penetration rate is:

$$\begin{gathered} ROP = -8.41 + 0.0612\,\beta + 0.0084\,WOB + 0.1506\,RPM - 0.00641\,Cs - 0.002441\,\beta\times\beta \\ - 0.000017\,WOB\times WOB - 0.000481\,RPM\times RPM + 0.000002\,Cs\times Cs + 0.000088\,\beta\times WOB \\ + 0.000464\,\beta\times RPM + 0.000001\,\beta\times Cs + 0.000010\,WOB\times Cs \end{gathered}$$

The results of the analysis of the variance of the penetration rate (Table 8) show that β×β is the interaction having the greatest effect on the total variation of the penetration rate, contributing 31.55%. The second greatest effect on the penetration rate is the interaction β×RPM, with a contribution of 12.11%, followed by compressive strength Cs and interaction WOB×Cs, with contributions of 9.41% and 6.87%, respectively. In contrast, the factor RPM, β and the interactions Cs×Cs, RPM×RPM, and β×WOB have very low contributions to the variation in penetration rate of 4.68%, 4.34%, 4.44%, 3.53%, and 2.40%. The WOB, (at 0.52%), and the interactions WOB×WOB (0.14%) and β×Cs (0.06%) do not have significant effects on the total variability of penetration rate.

Table 8 ANOVA results for penetration rate (ROP)

Source	DF	AdjSS	AdjMS	F-Value	P-Value	P_C%
Regression	12	17.1073	1.42561	30.81	0.000	/
β	1	0.1410	0.14096	3.05	0.103	4.34
WOB	1	0.0168	0.01682	0.36	0.556	0.52
RPM	1	0.1522	0.15219	3.29	0.091	4.68
Cs	1	0.3058	0.30582	6.61	0.022	9.41
β×β	1	1.0250	1.02497	22.15	0.000	31.55
WOB×WOB	1	0.0046	0.00463	0.10	0.756	0.14
RPM×RPM	1	0.1147	0.11475	2.48	0.138	3.53
Cs×Cs	1	0.1444	0.14437	3.12	0.099	4.44
β×WOB	1	0.0780	0.07796	1.69	0.215	2.40
β×RPM	1	0.3933	0.39329	8.50	0.011	12.11
β×Cs	1	0.0019	0.00193	0.04	0.841	0.06
WOB×Cs	1	0.2233	0.22326	4.83	0.045	6.87
Error	14	0.6477	0.04627			
Total	26	17.7551				

Figure 9 show the relationships between actual and predicted response values for ROP. The presented quadratic regression model provided a very good statistical performance with high correlation coefficients of 0.9635 between the actual and predicted values of the penetration rate.

Finally, as shown in Figure 10, for normal probability of the residuals of the penetration rate model, it is found that the residuals are in a reasonably straight line, which may lead to the conclusion that the errors have a normal distribution. As a consequence, the penetration rate model is significant.

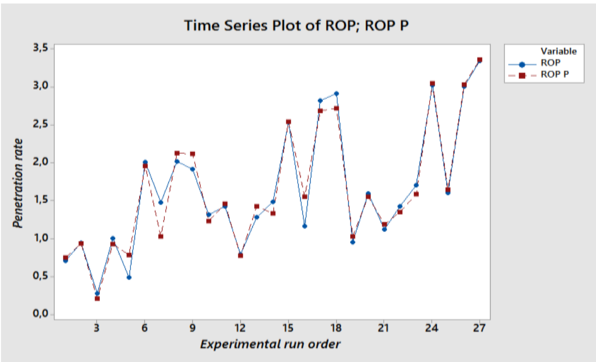

Figure 9 Experimental values and predicted values of penetration rate (ROP)

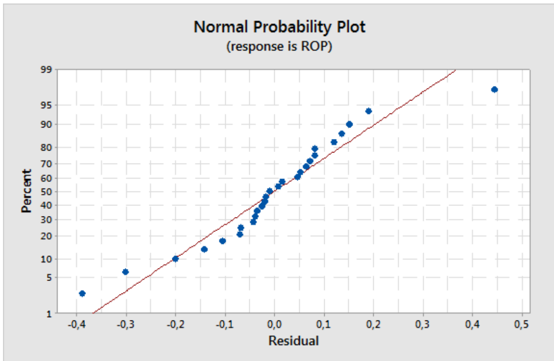

Figure 10 Potential normal distribution plot of the residuals for penetration rate (ROP)

4.4. Validation of Experiment

A confirmation experiment was performed with optimal level result of 3.48 mm/s. Table 9 shows the error difference between the predicted and experimental responses. It can be observed that for reliable statistical analysis, error values should be less than 20% (Cetin et al., 2011), so error percentages are within acceptable limits. Therefore, it can be deduced that the proposed empirical model can successfully predict ROP during drilling process.

Table 9 error difference between the predicted and experimental responses

Penetration rate	Taguchi	Experimental	Error %
Initial $A_1B_1C_1D_1$	0.877778	0.71	19.11
Optimal $A_3B_3C_3D_1$	3.52222	3.48	1.20

5. CONCLUSION

In this study, the Taguchi technique is used to obtain optimal drilling parameters in the drilling of different rocks under dry conditions. The experimental results were evaluated using S/N ratio, Pareto variance analysis, and regression analysis.

The following conclusions can be drawn: (1) As a result of the Taguchi experimental it was found that the interactions $\beta\times\beta$ and $\beta\times RPM$ were the most significant factors affecting the penetration rate, with percentage contribution of 31.55% and 12.11%, respectively; (2) The optimum control factors for penetration rate $\beta_3 WOB_3 RPM_3 Cs_1$ were β_3 = 45°, WOB_3 = 160 kgf, RPM_3 = 152 rpm, and Cs_1 = 640 kgf/cm^2; (3) ANOVA Pareto analysis showed that WOB and Cs have positive effects on penetration rate; (4) The quadratic mathematical model is developed with a confidence interval of 96.35 for the prediction of penetration rate (ROP).

In this study, the Taguchi technique was successfully applied both to determining the optimal combinations of drilling parameters and also to minimize costs and the number of drilling experiments.

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