Sādhanā Vol. 39, Part 5, October 2014, pp. 1055–1070. © Indian Academy of Sciences

Application of Taguchi method for cutting force optimization in rock sawing by circular diamond sawblades

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MS received 29 March 2013; revised 15 January 2014; accepted 21 April 2014

Abstract. In this paper, an optimization study was carried out for the cutting force (F_c) acting on circular diamond sawblades in rock sawing. The peripheral speed, traverse speed, cut depth and flow rate of cooling fluid were considered as operating variables and optimized by using Taguchi approach for the F_c. $L_{16}(4^4)$ orthogonal array was chosen for the experimental trials based on the operating variables and their levels. The signal-to-noise (S/N) ratios and the analysis of variance (ANOVA) were employed to determine optimum cutting conditions and significant operating variables, respectively. The F_c was also modelled based on the operating variables using regression analysis. The developed model was then verified using various statistical approaches. The results revealed that the operating variables of circular diamond sawblades can be precisely optimized by Taguchi approach for the F_c in rock sawing. The cut depth and peripheral speed were statistically determined as the significant operating variables affecting F_c. Furthermore, the modelling results showed that the proposed model can be effectively used for the prediction of F_c in practical applications.

Keywords. Rock sawing; cutting force; Taguchi application; optimization; modelling.

1. Introduction

The use of natural stones as a construction and building material has been increasing worldwide. As a result of this increase, there has been recently more attention for sustainability during their productions (Karakurt *et al* 2012). Circular diamond sawblades have been successfully used in sawing of almost all types of natural stones due to their distinctive advantages over other traditional cutting tools (Ersoy *et al* 2005).

As in the case of other machining tools, the cutting performances of circular diamond sawblades are affected by the complex interaction of many effective parameters as given in table 1 (Yousefi *et al* 2010). Despite these parameters affecting the cutting performances, circular diamond sawblades have been subjected to various studies in the existing literature. These studies can be mainly grouped as sawing mechanisms, saw design, relationships between sawability and rock properties. Kahraman & Gunaydin (2008), Atıcı & Ersoy (2009), Aslantas *et al* (2009),

Table 1. Effective parameters in sawing process.

Non-controlled parameters related to the rock characteristics		Partially controlled or controlled parameters	
Mechanical properties	Uniaxial compressive strength	Sawing characteristics	Force on saw
	Tensile strength		Traverse speed
	Bending strength		Specific removal rate
	Young's modulus		Peripheral speed
	Hardness		Depth of cut
	Abrasiveness		Specific energy
	Water content		Cutting mode
Textural properties	Grain size	Saw design	Diamond properties
	Grain shape		Matrix properties
	Mineral type and content		Machine vibration
	Degree and type of cementation		Operator skill
	Bonding		
	Matrix type and content	Working conditions	Machine power
			Amount of water used
Structural properties	Joints and fractures		Environment / climate
	Degree of alteration		
	Cleavages		

Buyuksagis (2010), Yousefi *et al* (2010), Guney (2011), Mikaeil *et al* (2011, 2013), Yılmaz *et al* (2011), Yılmaz (2011), Ucun *et al* (2011), Ataei *et al* (2012), Yaşıtlı *et al* (2012), Turchetta (2012), Aydin *et al* (2013a, b, c), Engin *et al* (2013), Bayram (2013), Karakurt *et al* (2013a, b) and Sengun & Altindag (2013) are among the most recently published papers in the existing literature. The studies indicate that the cutting performances of circular sawblades have been well-documented. However, further studies aiming at establishing standards for the cutting performances of circular diamond sawblades in rock sawing are still required due to the complex nature of the rock material. On the other hand, stone producers want to know the sawability degree of a particular rock being cut for the cost estimation and planning of the plants. Thus, selection of suitable operating variables and proper sawing result can decrease in the production costs and can increase in productivity. Therefore, it is highly important to optimize the sawing processes for improving the productivity and decreasing the production costs. Additionally, although it has been successfully used for determination of the optimum operating variables in various industries, no application of the Taguchi method in rock sawing by circular diamond sawblades has been reported so far. Therefore, an optimization study for the F_c acting on diamond sawblades in rock sawing using Taguchi approach is presented in this study. The study mainly aims at applying the Taguchi method for the determination of optimum operating variables to minimize the F_c affecting directly the tool wear, cutting temperatures, and surface integrity in sawing processes. A predictive model for the F_c is also proposed using regression analysis based on the operating variables.

2. The Taguchi methodology

Statistical experimental design methods provide a systematic and efficient plans for experimentation to achieve certain goals so that many control factors can be simultaneously studied.

Taguchi's approach is totally associated with the statistical design of experiments. The Taguchi method, established by Genichi Taguchi has been generally adopted to optimize the design variables since this method can significantly reduce the overall testing time and the costs (Wang & Huang 2007). Three major tools which are used in the Taguchi method are the orthogonal arrays (OA's), analysis of variance (ANOVA) and the signal (S) to noise (N) ratios (S/Ns). Taguchi method utilizes OA's from experimental design theory to study a large number of variables with a small number of experiments. An OA consists of rows and columns. Each column of the OA represents a variable assigned, while each row of the OA represents a run or level of the variables to be applied (Nik *et al* 2012). Depending on the number of variables and levels required,

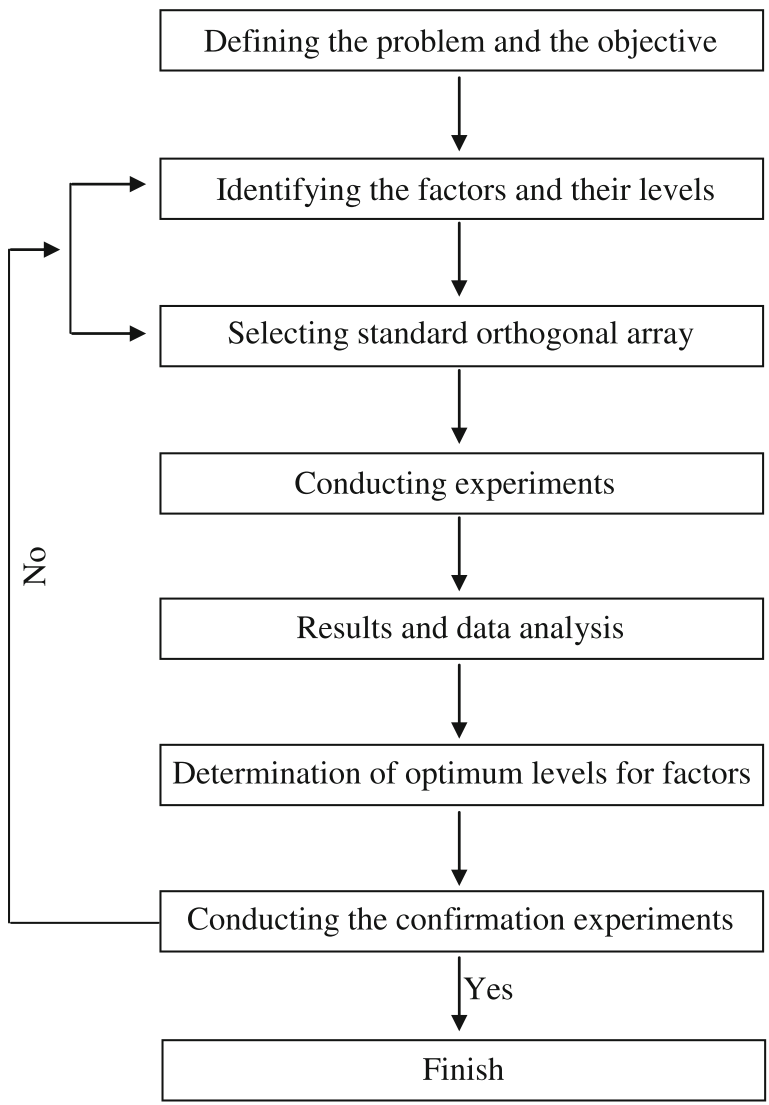

Figure 1. A flowchart of the Taguchi application.

the users can select the standard orthogonal arrays designed specifically and conduct the experiments. On the other hand, ANOVA is a matrix of numbers arranged in rows and columns. Each row represents the levels of variable in each run and each column represents a specific level for a variable that can be arranged for each run (Adnani *et al* 2010). The S/N ratios are a useful concept to characterize the response of any particular engineering system to external influences. In other words, ANOVA and the S/N ratios are used to evaluate the experimental results. A flowchart of the Taguchi application for the optimization studies is presented in figure 1. The S/N ratios can be divided into three categories as shown below when the characteristic is continuous: (1) nominal is the best (NB), (2) smaller is the better (SB), (3) larger is the better (LB) (Ghani *et al* 2004).

$$\text{Nominal is the best: } S/Ns = 10\log\frac{\bar{y}}{s_y^2}, \tag{1}$$

$$\text{Smaller is the best: } S/Ns = -10\log\frac{1}{n}\left(\sum y^2\right), \tag{2}$$

$$\text{Larger is the best: } S/Ns = -10\log\frac{1}{n}\left(\sum \frac{1}{y^2}\right), \tag{3}$$

where $\bar{y}$ is the average observed data, s_y^2 is the variance of y, n is the number of observations, and y is the observed data. In all cases, the higher the S/N ratio, the better is the result.

3. Experimental study

3.1 *Material*

In this study, a pre-dimensioned granitic rock was used for the sawing experiments. Each rock sample has a thickness of 3 cm, length of 30 cm and width of 10 cm. The mineralogical and petrographical properties of the sample were determined through thin section studies and the point-count method (see figure 2). The mineralogical compositions of the rock are given in table 2 along with its textural and granular descriptions. As can be followed from table 2, K-feldspar, quartz, plagioclase and biotite are the main rock-forming minerals of the used rock. Additionally, grain size distribution of the rock-forming minerals was also determined using digital image processing software of DeWinter Material Plus 4.1. Some physico-mechanical properties of the tested rock were determined according to the related ISRM (1981) suggested methods (see table 3).

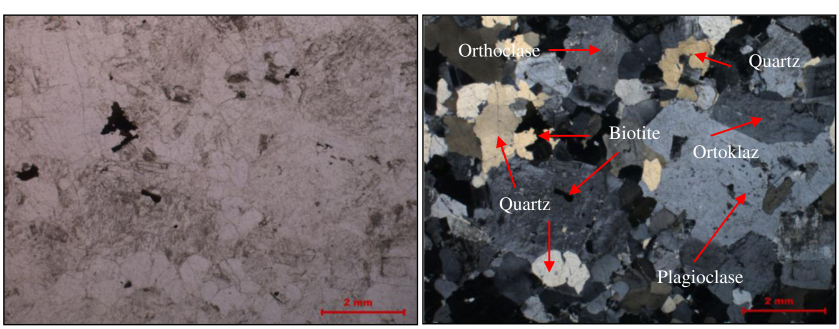

Figure 2. Thin section studies of the tested rock.

Table 2. Mineralogical and petrographic description of the rock used in the experiments.

Mineral	Grain size (mm) Min	Max	Mean	Proportion (%)
Alkali feldspars (orthoclase. microcline)	0.48	4.80	0.8	39
Quartz	0.24	2.24	1.7	27
Plagioclase	0.56	3.60	2.0	22
Biotite	0.32	1.60	0.4	10
Secondary components	0.08	0.56		2
Petrographic descriptions	Rock name: Alkali granite. Granular, hypidiomorphic texture, coarse-grained, grains between 0.08 mm and 4.80 mm, and the coarsest grain is observed in alkali feldspar mineral. Alkali feldspar, quartz and plagioclase are the predominant minerals, opaque minerals are the accessories, small amount of biotite is observed. Alkali feldpars have perthitic texture and altered to clay. Typically showing twinning, microcline minerals altered to clay. Anhedral quartz, plagioclase show polysynthetic twinning, they are prizmatic and slightly altered to clay.			

3.2 *Experimental design*

Once the problems and objectives of the study are defined, the next two steps include the determination of the operating variables and their levels that influence the performance characteristics and conducting the experiments in the design of philosophy of Taguchi. Therefore, a total of four operating variables, each varied at four levels was selected in the current study. These operating variables are the peripheral speed, the traverse speed, the cut depth and the flow rate of cooling fluid. Their levels were selected based on preliminary sawing tests by considering instructions of diamond disc manufacturers and related literatures. Tap water was used as the cutting fluid. The selected operating variables and their levels are given in table 4. Based on the operating variables and their levels, a standard orthogonal array of $L_{16}(4^4)$ was found to be appropriate for the experimental layout which requires 16 trials (see table 5). S/N ratios which are a statistical measure of performance in Taguchi method was subsequently used to analyse the results.

Table 3. Physico-mechanical properties of the rock used in the experiments.

Rock properties	Value
Density (kN/m^3)	25.9
Water absorption by volume (%)	0.86
Porosity (%)	1.50
Ultrasonic velocity (m/s)	4140
Cerchar abrasion Index	5.2
Schmidt hammer hardness	56
Microhardness (HV)	539.55
Shore hardness	75.6
Mohs hardness scale	4.5

Table 4. Operating variables and their levels used in the experimentations.

Operating variables	Symbol	Level			
Peripheral speed (m/s)	A	25	30	35	40
Traverse speed (cm/min)	B	40	50	60	70
Cutting depth (cm)	C	0.5	1.0	1.5	2.0
Flow rate of cooling fluid (ml/s)	D	50	100	150	200

Here, the term signal (S) represents desirable value (mean), and noise (N) represents undesirable value (standard deviation from mean) for the results. Specifically, the smaller and the better characteristics form for S/N were selected since the lower values of cutting force were desired in sawing applications. The S/N ratios of the smaller the better performance characteristic were then calculated thorough the equation below using MiniTAB statistical software.

$$S/Ns = -10 \log \frac{1}{n}\left(\sum y^2\right), \tag{4}$$

where n is the number of tests, y is the observed data.

3.3 *Experimental set-up*

A computer-aided circular diamond sawblades were used for sawing experimentations as shown in figure 3. The circular diamond sawblades consist of three major sub-systems: a cutting unit, instrumentation and a personal computer (PC). The diamond sawblade used in the tests was of 40 cm diameter, having 28 impregnated diamond segments (circumferential length 40 mm, width 3.5 mm and height 10 mm). The diamonds were sized at 40/50 US mesh with a concentration of 30 which is recommended for the sawing of hard materials. Sawblade movements,

Table 5. Experimental layout for $L_{16}(4^4)$ orthogonal array including the operating variables.

		Operating variables			
Trials	Designation	A (m/s)	B (cm/min)	C (cm)	D (ml/s)
1	$A_1B_1C_1D_1$	1	1	1	1
2	$A_1B_2C_2D_2$	1	2	2	2
3	$A_1B_3C_3D_3$	1	3	3	3
4	$A_1B_4C_4D_4$	1	4	4	4
5	$A_2B_1C_2D_3$	2	1	2	3
6	$A_2B_2C_1D_4$	2	2	1	4
7	$A_2B_3C_4D_1$	2	3	4	1
8	$A_2B_4C_3D_2$	2	4	3	2
9	$A_3B_1C_3D_4$	3	1	3	4
10	$A_3B_2C_4D_3$	3	2	4	3
11	$A_3B_3C_1D_2$	3	3	1	2
12	$A_3B_4C_2D_1$	3	4	2	1
13	$A_4B_1C_4D_2$	4	1	4	2
14	$A_4B_2C_3D_1$	4	2	3	1
15	$A_4B_3C_2D_4$	4	3	2	4
16	$A_4B_4C_1D_3$	4	4	1	3

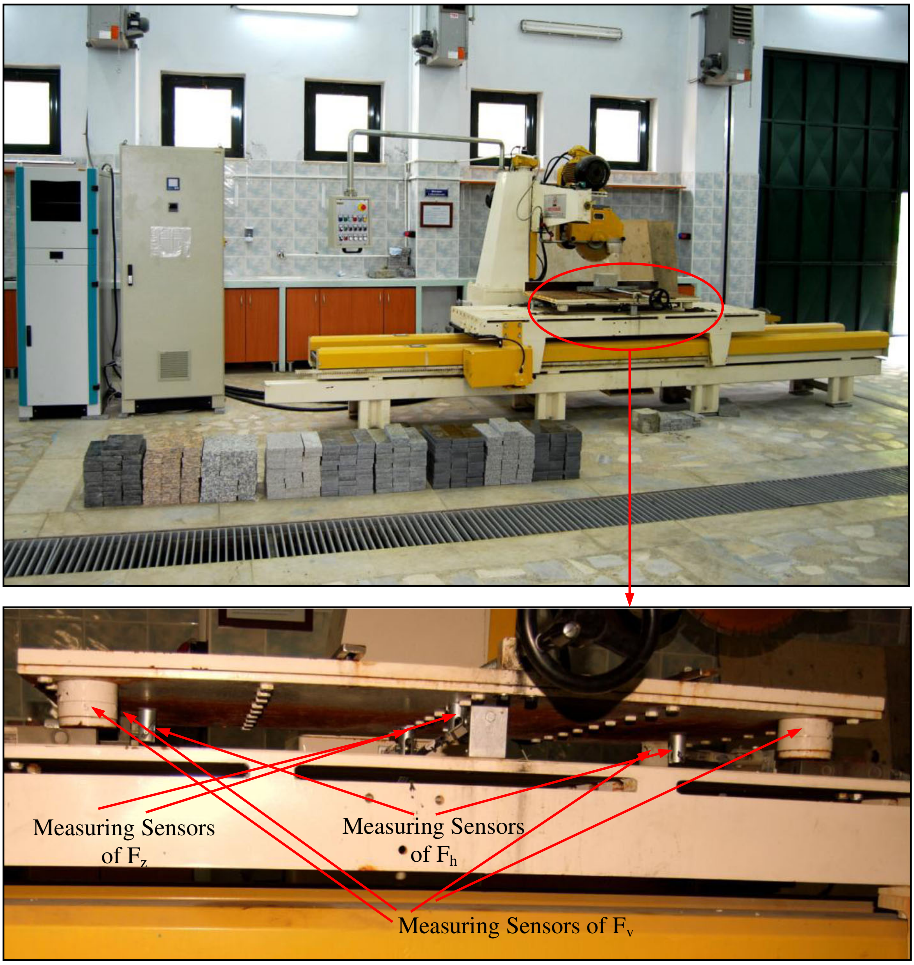

Figure 3. A view of circular diamond sawblades used for the experimentations.

forward–backward in the horizontal plane and up–down in the vertical plane, were driven with two 0.75 kW ac motors, while the turn of the disc were driven with 4 kW ac motor. Moreover, 0.75 kW ac motor was used to move the wagon through the cutting line. Operating variables, vertical, horizontal, and axial forces were measured using sensors, load cells, transducers and an encoder in the monitoring system. The force measuring sensors were modelled as SBS 500 kg C3 and STCS 100 kg C3 for vertical, horizontal and axial forces, respectively. The accuracy of the measured forces from those force sensors is ±0.01 kg. All movements of the cutting tools were controlled by the computer and industrial electronic cards. Transmissions to the computer were carried out using processing software.

3.4 *Experimental procedure*

The diamond sawblade was firstly dressed by cutting a siliceous sedimentary tuff block before the cutting tests. Afterwards, the sawing experiments were conducted. The rock sample was subjected to saw through its length. Due to the variability and accuracy of the experimental data, the sample was sawn four times at the same conditions. All cutting experiments were conducted in the down-cutting mode. The horizontal (F_h) and vertical (F_v) force components acting on the disc were measured using load cells. The tangential (F_t) and normal (F_n) force were derived from the Eqs. (6–16) considering the geometrical relations presented in figure 4 (Konstanty 2002; Tönshoff & Apmann 2002).

$$\text{Cos}\ \delta = \frac{F_v}{F_c}, \tag{5}$$

$$\text{Sin}\ \delta = \frac{F_h}{F_c}, \tag{6}$$

$$F_n = F_c \,\text{Cos}\,[(k\varphi) - \delta]\,, \tag{7}$$

$$F_n = F_c\left[Cos(k\phi)\frac{F_v}{F_c} + Sin(k\phi)\frac{F_v}{F_c}\right], \tag{8}$$

$$F_n = F_v \,\text{Cos}\,(k\varphi) + F_h \,\text{Sin}\,(k\varphi)\,, \tag{9}$$

$$F_t = F_c \,\text{Sin}\,[(k\varphi) - \delta]\,, \tag{10}$$

$$F_t = F_c\left[Sin(k\phi)\frac{F_v}{F_c} - Cos(k\phi)\frac{F_h}{F_c}\right], \tag{11}$$

$$F_t = F_v \,\text{Sin}\,(k\varphi) - F_h \,\text{Cos}\,(k\varphi)\,, \tag{12}$$

$$F_c = \sqrt{F_n^2 + F_t^2}, \tag{13}$$

where: F_h; the horizontal force (N), F_v; the vertical force (N), F_z; the axial force (N), F_n; the normal force (N), F_t; the tangential force (N), F_c; the resultant cutting force (N), D_s; the disc diameter (mm), d; the cutting depth (mm), V_c; the workpiece traverse speed (m/s), V_p; the peripheral speed (m/s), φ; the total included angle of the contact zone (degrees) and kφ; is the angle showing the location of the resultant force (degrees). The total included angle of the contact

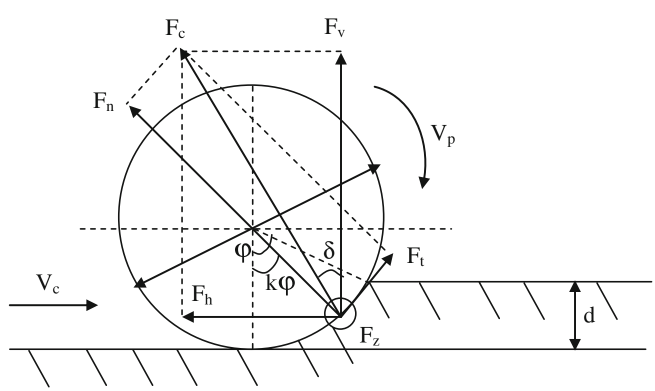

Figure 4. The kinematics of cutting process for the down-cutting model.

zone (φ) and the angle (kφ) indicating the location of the resultant force can be calculated by the following equations:

$$\varphi = \cos^{-1}\left(1 - \frac{2d}{D_s}\right), \tag{14}$$

$$k\varphi = 0.7\varphi. \tag{15}$$

3.5 *Optimization studies*

Analysi s of mean (ANOM) approach was adopted to develop the optimum conditions. The mean of the S/N ratios of each factor at a certain level can be calculated using the equation below(Chou *et al* 2010).

$$(M)_{Factor=l}^{Level=i} = \frac{1}{n_{li}} \sum_{j=1}^{n_{li}} \left[\left(\frac{S}{N}\right)_{Factor=l}^{Level=i} \right]_j, \tag{16}$$

where n_{li} is the number of appearances of factor I in the level i, and $[(\text{S/N})\ \text{factor}^{Level=i} = I]_j$ is the S/N ratio of factor I in level i, and its appearance sequence in table is the *jth*. Thus, the S/N response was obtained together with the optimum conditions. Additionally, to define which operating variables significantly affect the quality characteristic, analysis of variance (ANOVA) was done. Finally, confirmation experiments under these optimum conditions were conducted.

4. Results and data analysis

4.1 *Optimum conditions*

The performance of circular diamond sawblades was evaluated for F_c with respect to the Eq. (14) and the results presented in table 6. Afterwards, the S/N ratios were then calculated. The maximum values of S/N ratios among the 16 trials were determined. ANOM was then produced

Table 6. Experimental results including the operating variables, their levels, results and S/N ratios.

Trials	A (m/s)	B (cm/min)	C (cm)	D (ml/s)	F_c (N)	Standard deviation	S/N ratios
1	25	40	0.5	50	67.95	2.41	−36, 64
2	25	50	1.0	100	132.20	4.80	−42.42
3	25	60	1.5	150	179.20	3.31	−45.07
4	25	70	2.0	200	212.81	5.88	−46.56
5	30	40	1.0	150	89.58	1.17	−39.04
6	30	50	0.5	200	55.99	1.36	−34.96
7	30	60	2.0	50	214.82	6.22	−46.64
8	30	70	1.5	100	151.36	5.37	−43.60
9	35	40	1.5	200	90.81	1.73	−39.16
10	35	50	2.0	150	123.81	2.72	−41.86
11	35	60	0.5	100	68.98	1.79	−36.77
12	35	70	1.0	50	133.77	3.01	−42.53
13	40	40	2.0	100	117.34	1.62	−41.39
14	40	50	1.5	50	151.29	4.35	−43.59
15	40	60	1.0	200	71.15	1.33	−37.04
16	40	70	0.5	150	48.11	1.72	−33.65*

* Indicates the maximum value of S/N ratios among the 16 trials

Table 7. S/N ratio response table for F_c.

Factor/level	S/N ratio $j = 1$	$j = 2$	$j = 3$	$j = 4$	ANOM
A/1	−36.64	−42.42	−45.07	−46.56	−41.92
A/2	−39.04	−34.96	−46.64	−43.60	−41.06
A/3	−39.16	−41.86	−36.77	−42.53	−40.08
A/4	−41.39	−43.59	−37.04	−33.65	−38.92*
B/1	−36.64	−39.04	−39.16	−41.39	−39.06*
B/2	−42.42	−34.96	−41.86	−43.59	−40.71
B/3	−45.07	−46.64	−36.77	−37.04	−41.38
B/4	−46.56	−43.60	−42.53	−33.65	−41.59
C/1	−36.64	−34.96	−36.77	−33.65	−35.51*
C/2	−42.42	−39.04	−42.53	−37.04	−40.26
C/3	−45.07	−43.60	−39.16	−43.59	−42.86
C/4	−46.56	−46.64	−41.86	−41.39	−44.11
D/1	−36.64	−46.64	−42.53	−43.59	−42.35
D/2	−42.42	−43.60	−36.77	−41.39	−41.05
D/3	−45.07	−39.04	−41.86	−33.65	−39.91
D/4	−46.56	−34.96	−39.16	−37.04	−39.43*

* Indicates the maximum value of the mean of the S/N ratios of a certain factor among the four levels

and given in table 7. Also, the maximum values of the mean of the S/N ratios of a certain factor among the four levels were determined. These values refer to the optimum conditions for F_c. Based on table 7, the optimum operating variables minimizing the F_c are the peripheral speed at level 4 (40 m/s), the traverse speed at level 1 (40 cm/min), the cut depth at level 1 (0.5 cm),

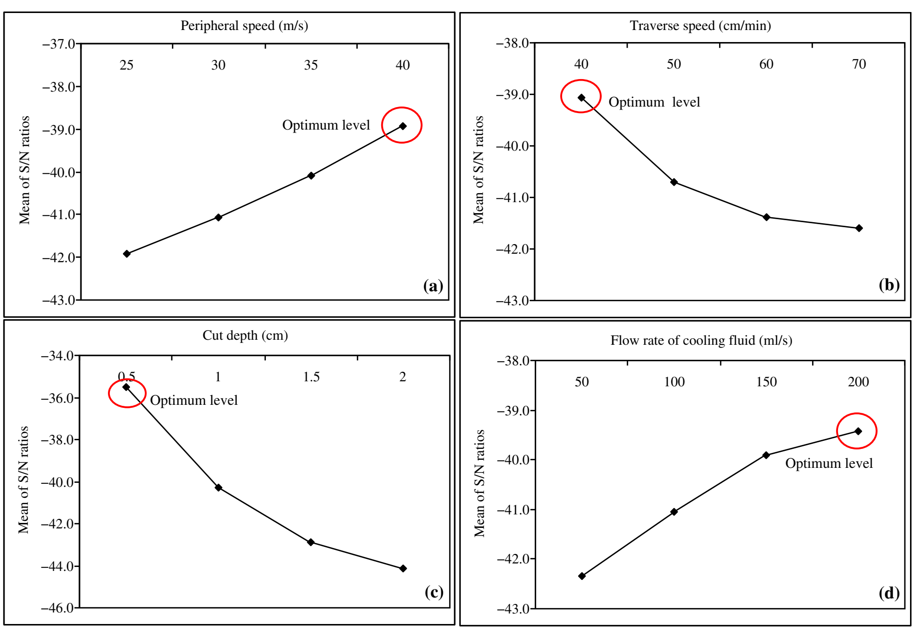

Figure 5. Effects of operating variables on the S/N ratio for the specific energy. (**a**) peripheral speed, (**b**) traverse speed, (**c**) cut depth and (**d**) flow rate of cooling fluid.

and the flow rate of cooling fluid at level 4 (200 ml/s). In this case, the designation for optimum operating variables was determined as $A_4B_1C_1D_4$.

4.2 *Influence of operating variables on the F_c*

The graphical illustrations of the S/N ratios are presented in figure 5. As shown, all variables have significant influences on the F_c but, their significance degrees vary. The cut depth, the peripheral speed and the flow rate of cooling fluid are more significant than the traverse speed has. The ANOVA analysis confirmed this observation as well (see table 8). The cut depth has the greatest influence on the F_c with the impact factor of 70.46%, followed by the peripheral speed. When the traverse speed and the cut depth increases, the F_c increases almost proportionally. On the other hand, the highest levels for the peripheral speed and the flow rate of cooling fluid appear to be the best choice to obtain the minimum value of F_c, whereas the lowest levels of the traverse speed and the cut depths appeared to be the optimum choices.

4.3 *Analysis of variance (ANOVA)*

An analysis of variance (ANOVA) of the experimental results was performed to evaluate the relative importance of the operating variables. This has been accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean of the S/N ratios, into contributions by each of the operating variables and the errors. The total sum of squared deviations SS_T from the total mean S/N ratios can be calculated as

$$SS_T = \sum_{i=1}^{n} (n_i - n_m)^2, \tag{17}$$

where n is the number of experiments in the orthogonal array and n_i is the mean of S/N ratios for the *ith* experiment. The total sum of spared deviations SS_T is decomposed into two sources: the sum of squared deviations SS_d due to each design parameter and the sum of squared error SS_e. The percentage contribution (%) can be then calculated as

$$C(\%) = \frac{SS_d}{SS_T}, \tag{18}$$

where SS_d is the sum of the squared deviations.

In the ANOVA, F ratio is commonly used to see which factor has a significant effect on the performance indicator. The F ratio is calculated from the statistical analysis and then compared

Table 8. Analysis of variance for F_c.

Source	Degree of freedom	Sum of squares	Mean squares	F ratio	Contribution (%)
A (m/s)	3	30.34	10.11	4.74*	12.30
B (cm/min)	3	15.73	5.24	2.46	6.38
C (cm)	3	173.82	57.94	27.15*	70.46
D (ml/s)	3	20.37	6.79	3.18	8.26
Error	3	6.40	2.13		2.60
Total	15	246.66			100

* Significant at confidence level of 95%. A: Peripheral speed, B: Traverse speed, C: Cut depth, D: Flow rate of cooling fluid.

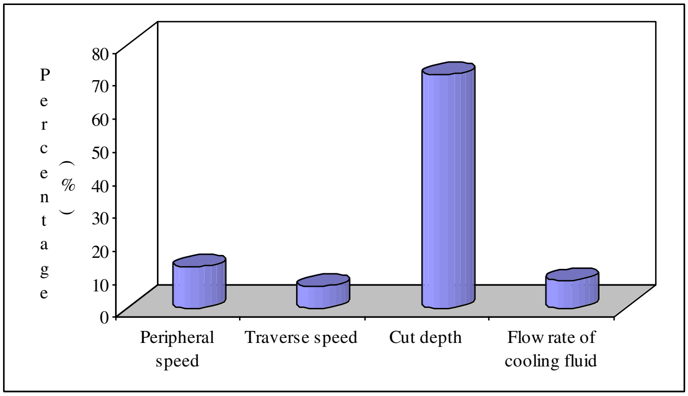

Figure 6. Variable percentage effect.

to the critical value. In performing the F test, the mean of squared deviations SS_m due to each design parameter needs to be calculated. The mean of squared deviations SS_m is equal to the sum of squared deviations SS_d divided by the number of degrees of freedom associated with the design parameter (Yang & Tarng 1998). If the F_{ratio} calculated is larger than the $F_{critical}$ value, it is an indication that the statistical test is significant at the confidence level selected. If not, it indicates that the statistical test is not significant at the confidence level. In addition, the higher F_{ratio} indicates that there is a considerable change on the performance characteristic due to the variation of the process parameters (Azmir & Ahsan 2008). Table 8 shows the results of ANOVA carried out in the current study. Based on the ANOVA table, the cut depth and peripheral speed were statistically determined as the significant operating variables affecting the F_c, while the others were statistically found insignificant since these operating variables could not pass the test. The percentage contributions of these operating variables are 70.46 and 12.30% for cut depth and peripheral speed, respectively. The contribution of each variable on the F_c is illustrated in figure 6.

4.4 *Confirmation tests*

As a final step in Taguchi method, the confirmation experiment is conducted for validation of the conclusions drawn during the analysis phase. The confirming experiments were conducted on the basis of optimum conditions of $A_4B_1C_1D_4$ and the results were presented in table 9. It was observed that the S/N ratios obtained from the optimum conditions is bigger (−30.86) than those in test 16 (−33.65) where the maximum value of S/N ratios among the 16 trials was produced. Accordingly, the F_c resulted from the optimum conditions is lower than that of test 16. In the relevant literature, 100 ml/s is the critical level for the flow rate of cooling fluid. When this value decreases, the chips produced may not be efficiently removed from the cutting area and this may lead to get higher cutting forces. Therefore, it is commonly recommended that the

Table 9. Results of confirmation test for optimization.

	A (m/s)	B (cm/min)	C (cm)	D (ml/s)	F_c (N)	S/N ratio
Trial 16	40	70	0.5	150	48.11	−33.65
Optimal conditions	40	40	0.5	200	45.32	−30.86

flow rate of cooling fluid must be above the critical values for achieving the effective cutting performances. When the optimum conditions are analysed, it is seen that the level of flow rate of cooling fluid increases from 150 to 200 ml/s indicating the value must be above the critical value for flow rate of cooling fluid. As a result, the results of confirmation experiment revealed that the F_c of the circular diamond sawblades in rock sawing could be improved through Taguchi approach.

4.5 *Prediction of the F_c from operating variables*

To establish a prediction model, the statistical software package *SPSS* was used to perform the regression analysis using the experimental data in table 6. In this analysis, the F_c and operating variables were considered as the dependent and independent variables, respectively. The regression model is given below (Eq. 19) and the dependent variable, the F_c, is seen as a linear function of all operating variables. The determination coefficient (R^2) of the model is 0.92. That means, 92% of the variation of the experimental data are explained by the equation.

$$F_c(N) = 88.294 - 3.536A + 1.530B + 71.461C - 0.221D, \tag{19}$$

where, F_c is the cutting force (N), A is the peripheral speed (m/s), B is the traverse speed (cm/min), C is the cutting depth (cm) and D is the flow rate of cooling fluid (ml/s).

Validation of the model was carried out by considering the behaviour of R^2, the t-and F-tests, the plots of observed vs. predicted F_c, and the pattern of residuals. In the analysis, the t-test was used to examine the significance of each variable in the model, while the F-test was used for the whole model significance at a 95 per cent significance level. If the calculated t-value is larger than the tabulated t-value, the variable is considered to be significant. Similarly, if the calculated F-ratio is larger than the tabulated F-ratio, the model is considered to be significant again at a 95 per cent significance level. The statistical results of the model are given in table 10 in detail. As seen, the calculated t-values for the variables involved in the model and the calculated F-ratio for the model are larger than the tabulated t-value and F-ratio, respectively confirming the significance of the model. When the predicted trends vs. the observed trends were examined, it could be disclosed that there was a high degree of relationship between the predicted and observed F_c (see figure 7). In other words, the developed model can give adequate predictions for the F_c for the conditions. Pattern of residuals presented in figure 7, can provide the direct comparison of model and real data. In the present study, the residuals seem to be randomly scattered about the line (x-axis). That means, the correctness of the model was statistically confirmed. Furthermore, the R^2 of the model is 0.92 indicating that the prediction model has a satisfactory goodness of fit.

Table 10. Statistical results of the regression model.

Independent variables	Coefficient	Standard error	Standard error of estimate	t-value	Tabulated t-value	F-ratio	Tabulated F-ratio	Determination coefficient (R^2)
Constant	88.294	35.836	17.257		2.464			
A (m/s)	−3.536	0.772		−4.582				
B (cm/min)	1.530	0.386		3.965	1.75	32.648	3.28	0.92
C (cm)	71.461	7.717		9.260				
D (ml/s)	−0.221	0.077		−2, 854				

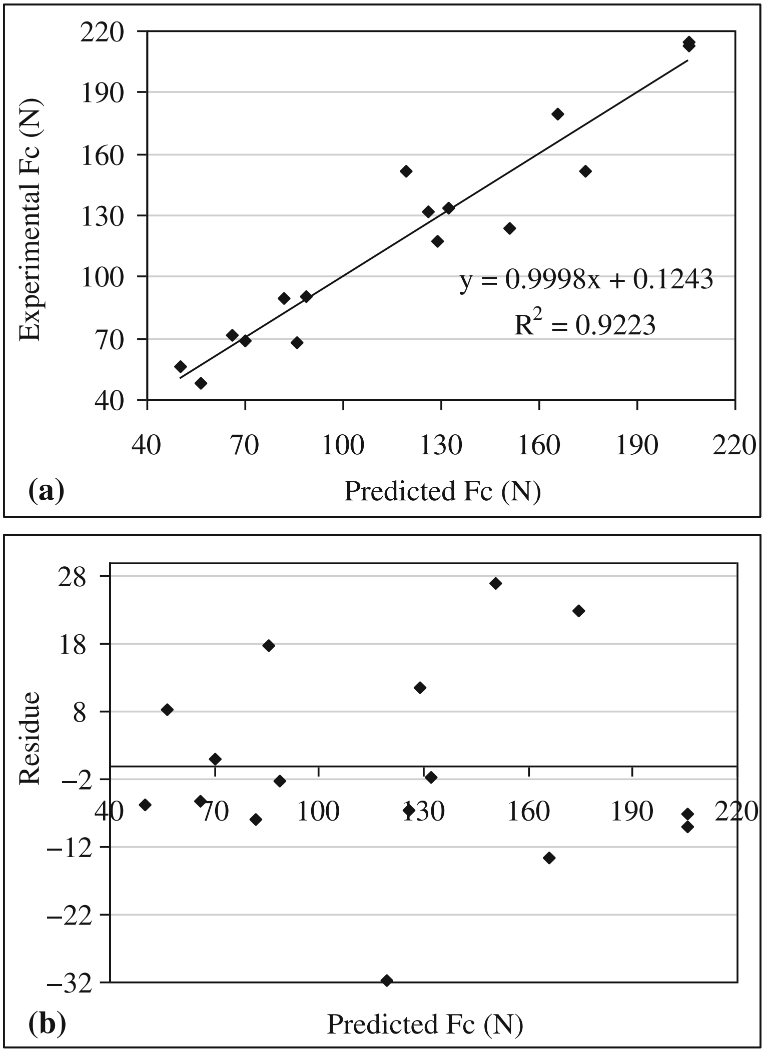

Figure 7. (**a**) Predicted F_c derived from operation variables vs. experimental F_c; (**b**) the plots of the residue against the predicted F_c values derived from the operating variables.

5. Conclusions

Using Taguchi method, the optimum conditions for obtaining minimum F_c were investigated for circular diamond sawblades in rock sawing. Most importantly, the current study examined the usability of Taguchi approach for the F_c optimization and prediction in circular sawing of rock. The results showed that the higher level of peripheral speed (40 m/s), the lower level of traverse speed (40 cm/min), the lower level of cut depth (0.5 cm) and the higher level flow rate of cooling fluid (200 ml/s) were determined as the optimum conditions minimizing the F_c. The cut depth and peripheral speed were statistically determined as the most significant operating variables affecting F_c, respectively. It was also disclosed that the proposed model can be used for the estimation of F_c in practical applications. In conclusion, the present study indicated that Taguchi approach is suitable for optimization of operating variables in rock sawing by circular diamond sawblades. Therefore, further studies aiming at optimization of other performance indicators of circular diamond sawblades in rock sawing such as specific energy, surface roughness and wear could be carried out by the Taguchi method.

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