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ORIGINAL ARTICLE

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Hole roundness in deep-hole drilling as analysed by Taguchi methods

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Abstract This work investigates the roundness of holes by application of Taguchi methods to BTA deep-hole drilling with reference to process factors. Taguchi methods and statistical techniques are used in experimental layout, in the analysis of each control factor, and in prediction of the optimum setting for control factors. A set of confirmatory tests is then conducted to verify the estimated response. Influences of the control factors are discussed, and the levels of factors that produce holes of desired roundness with sufficient robustness are presented.

Keywords BTA deep-hole drilling · Control factor · Roundness · Taguchi methods

Nomenclature

d	Tool diameter, mm
ℓ	Shaft length, mm
Δz	Feed rate, mm/rev
n	Rotational speed, rpm
R	Roundness error of hole, mm
DF	Degree of freedom
SS	Sum of squares
F	Fisher statistic
V	Mean square
ϱ	Percent contribution

1 Introduction

Deep-hole drilling is a complex machining process in which the ratio of hole depth to hole diameter exceeds 10. Hence the stiffness of the tool shaft is weakened by its own length, which makes the tool shaft susceptible to deflection and thus causes inaccuracies in the machined hole, affecting the roughness of the surface and the roundness of the hole. Often, the user must adjust various machining conditions to obtain a hole of high quality. It is always desirable to configure suitable machining conditions to get optimised machining quality.

The quality of machining in deep-hole drilling has been studied under various machining conditions [1–5]. These studies employed the one-variable-at-a-time technique, which is time consuming and incapable of yielding conclusions that are associated with a statistical level of confidence [6]. It is desirable to select a combination of optimum machining conditions to produce holes of good quality. The Taguchi method is used here to study the multi-variable process and to serve the purpose of condition optimisation. This method is economical because fewer experiments are needed than required by the one-variable-at-a-time method; moreover, the conclusions can be associated with a statistical level of confidence [7, 8].

This work investigates the roundness of holes by application of Taguchi methods to BTA deep-hole drilling with reference to process factors. The machining conditions tool diameter, shaft length, feed rate and rotational speed influence the roundness of holes in deep-hole drilling. Five control factors were used in a modified L8 orthogonal array design. The signal-to-noise (S/N) ratios are derived from the lower-the-better roundness error because to obtain optimal machining quality, the minimum roundness error of a hole is desired. Therefore, the lower-the-better roundness error should be selected. An analysis of variance (ANOVA) was performed to determine the effect of the control factors. The optimal level combination of control factors was selected from high S/N ratios. The final step is to predict and verify the quality characteristic.

2 Experimental technique

A series of experiments were performed on a retrofitted machine (Fig. 1) which can perform BTA deep-hole drilling to examine

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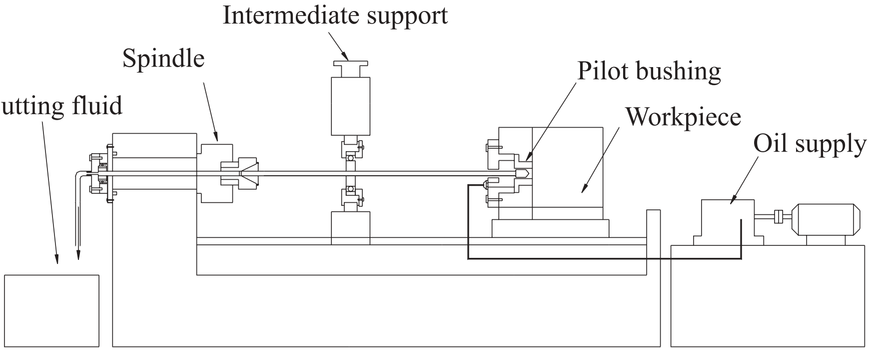
Fig. 1. BTA drilling system



the dynamic effects of a long tool shaft on the roundness of a drilled hole. The machine has an external cutting fluid supply and internal chip transport. The tool head is screwed onto the tool shaft, and cutting fluid is supplied through the space between the tool shaft and the machined hole and then removed along with the chips through the tool shaft. The cross section of the tool shaft is round.

The workpiece material was AISI 1045 steel with dimensions of ϕ 50 × 300 mm. The workpiece was drilled to a depth of 220 mm and cut into four equal pieces (about 50 mm long) after the drilling test.

An analysis of BTA drilling showed that the machining conditions tool diameter, shaft length, feed rate and rotational speed affect the quality of the hole profile. A tool of large diameter is screwed onto a shaft of large diameter (Appendix A), which creates larger stiffness of shaft than a smaller tool diameter. The shaft length dimension corresponds to the tool diameter dimension (Appendix A), but two-shaft lengths (1200 and 1600 mm) were used to relate the shaft length to the hole quality characteristics. A higher feed rate or rotational speed creates a higher machining rate but degrades the quality of the hole profile [1]. After all the trials are completed, the roundness of the hole is measured along its length (50, 100, 150 and 200 mm). The instrument for measuring roundness is the Mitutoyo (RA-2 type), which utilises the least square circle method (LSC) to express the hole profile. Figure 2 shows a sample of the roundness error of the hole.

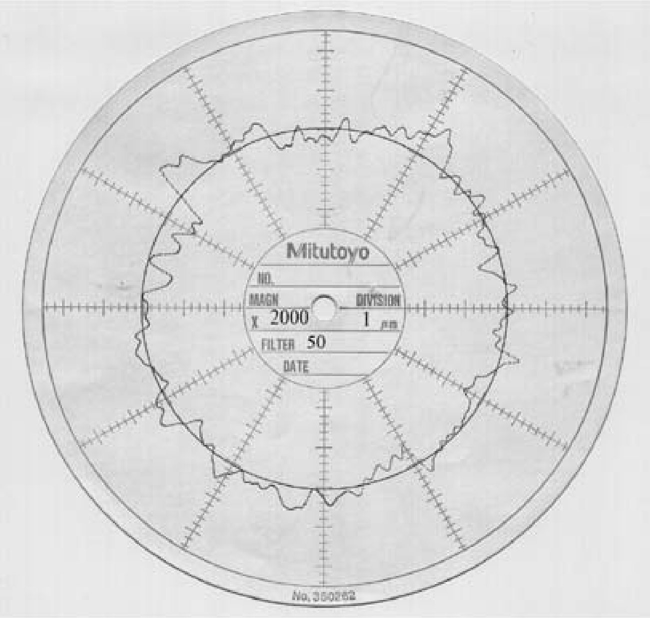


Fig. 2. Roundness error of hole: 0.0075 mm. Tool diameter: 18.91 mm, shaft length: 1600 mm, feed rate: 0.10 mm, rotational speed: 855 rpm, hole depth: 50 mm

3 Taguchi experiment: design and analysis

3.1 Orthogonal array experiment

Classical experimental design methods are time consuming. Many experiments must be performed when the number of control factors is high. Taguchi methods [7] use a special design of orthogonal arrays to study the entire factor space with only a small number of experiments. Table 1 lists the five control factors (four machining factors and one noise factor) and the two selected levels analysed in this study. The levels were assigned randomly and the limits used were determined from preliminary experiments. Table 2 specifies the experimental layout: 1 and 2 refer to the levels 1 and 2 of each control factor, respectively. A basic L8 orthogonal array can be established for use in this experimental analysis [7]. Furthermore, a two-level outer array was used to study the effect of the day-to-day variation (noise) of the BTA drilling process and to provide an independent estimate of experimental error in the testing of the main effects. Each experimental trial involved four-measurement data at each noise level. The roundness of the hole in the workpiece was measured at depths of 50, 100, 150 and 200 mm. Table 3 lists the

Table 1. Control factors and levels for the BTA drilling experiment

Symbol	Control factor	Level 1	Level 2
A	Tool diameter, d (mm)	18.91	26.40
B	Shaft length, ℓ (mm)	1200	1600
C	Feed rate, Δz (mm/rev)	0.05	0.10
D	Rotational speed, n (rpm)	390	855
N	Day of the week (noise)	Day 1	Day 2

Table 2. Experimental layout

Trial no.	Control factor				Noise N	
	A	B	C	D	I	II
1	1	1	1	1	$***$	$***$
2	1	1	1	2	$***$	$***$
3	1	2	2	1	$***$	$***$
4	1	2	2	2	$***$	$***$
5	2	1	2	1	$***$	$***$
6	2	1	2	2	$***$	$***$
7	2	2	1	1	$***$	$***$
8	2	2	1	2	$***$	$***$

$***$ Measurement data

Table 4. Roundness error S/N ratios

Trial no.	Control factor				S/N ratios (dB)	
	A	B	C	D	Day 1	Day 2
1	1	1	1	1	$\eta_{11} = 56.75$	$\eta_{21} = 55.89$
2	1	1	1	2	$\eta_{12} = 52.38$	$\eta_{22} = 52.83$
3	1	2	2	1	$\eta_{13} = 49.81$	$\eta_{23} = 49.42$
4	1	2	2	2	$\eta_{14} = 43.68$	$\eta_{24} = 43.50$
5	2	1	2	1	$\eta_{15} = 53.96$	$\eta_{25} = 54.86$
6	2	1	2	2	$\eta_{16} = 50.01$	$\eta_{26} = 49.56$
7	2	2	1	1	$\eta_{17} = 56.47$	$\eta_{27} = 55.35$
8	2	2	1	2	$\eta_{18} = 54.26$	$\eta_{28} = 54.53$

Where η_{ij} is the η value of each experiment, $i =$ day of experiments, $j =$ trial no.

data collected on two consecutive days. The table shows that the roundness errors on the two days differ slightly for a given level of control factor; the difference is due to experimental variation associated with dynamic effects in the BTA drilling process.

3.2 Signal-to-noise ratios

The Taguchi method uses the signal-to-noise (S/N) ratio instead of the average to convert the trial result data into a value for the characteristic in the optimum setting analysis. The S/N ratio reflects both the average and the variation of the quality characteristic. The S/N ratio for the lower-the-better quality characteristic on the roundness error of the hole must be taken, because to obtain optimal machining quality the minimum roundness error of hole is desired. Therefore, the lower-the-better roundness error should be selected. The η value of the S/N ratio is calculated according to [7]

$$\eta = -10 \log_{10} \left(\frac{1}{r} \sum_{i=1}^{r} y_i^2 \right) , \tag{1}$$

where r is the number of measurements made on the workpiece (in this study, $r = 4$) and y_i is the measured roundness error value. Based on the roundness error value in Table 3 and using Eq. 1, the S/N ratios are calculated and shown in Table 4; the table shows that a small roundness error creates a high S/N ratio and vice versa. For example, trial 4 in Table 3 had the largest roundness error on both days, which corresponded to the smallest S/N ratio in Table 4.

The influence of each control factor (A, B, C, D and N) on the roundness error was analysed from the S/N ratio response table, which expresses the S/N ratio at each level of control factor. The control factor influence is determined by its level difference values. A bigger control factor level difference means a greater influence on the roundness error of the hole. The influence of level k of factor P and the level difference between level 1 and level 2 of factor P can be calculated as follows:

$$\text{Level } k_P = \frac{\sum \eta_{P_k}}{8} \tag{2}$$

$$\text{Level difference}|_P = |\text{level } 1_P - \text{level } 2_P| , \tag{3}$$

Table 3. Roundness error of hole of BTA drilling for different day

Trial no.	Factor and column no.				Day	Roundness error, R (mm)			
	A	B	C	D		50 mm	100 mm	150 mm	200 mm
1	1	1	1	1	Day 1	0.0016	0.0015	0.0013	0.0014
					Day 2	0.0018	0.0016	0.0015	0.0015
2	1	1	1	2	Day 1	0.0026	0.0025	0.0023	0.0022
					Day 2	0.0025	0.0024	0.0022	0.0020
3	1	2	2	1	Day 1	0.0035	0.0033	0.0030	0.0031
					Day 2	0.0036	0.0035	0.0032	0.0032
4	1	2	2	2	Day 1	0.0075	0.0069	0.0060	0.0060
					Day 2	0.0071	0.0068	0.0065	0.0063
5	2	1	2	1	Day 1	0.0022	0.0020	0.0020	0.0018
					Day 2	0.0020	0.0019	0.0017	0.0016
6	2	1	2	2	Day 1	0.0033	0.0034	0.0030	0.0029
					Day 2	0.0035	0.0033	0.0034	0.0031
7	2	2	1	1	Day 1	0.0016	0.0015	0.0015	0.0014
					Day 2	0.0019	0.0018	0.0016	0.0015
8	2	2	1	2	Day 1	0.0022	0.0020	0.0019	0.0016
					Day 2	0.0020	0.0019	0.0019	0.0017

where level k_P is the influence of level k ($k = 1, 2$) of factor P ($P = A, B, C, D$ and N) and η_{P_k} is the η value of level k of factor P. Based on the η value in Table 4 and using Eqs. 2 and 3, the influence of all control factors and level differences can be calculated as shown in Table 5. The control factor influence hierarchy is C (feed rate), D (rotational speed), A (tool diameter) and B (shaft length). The control factor N (noise) has a weak influence on the S/N ratio in BTA drilling. Furthermore, the feed rate is the most influential process factor since it has the highest level of difference among all control factors.

Response graphs more clearly plot the influence of each control factor. A response graph shows the change of the S/N ratio when the control factor is changed from level 1 to level 2. The slope of the line determines the power of the control factor influence. Figure 3 displays response graphs for all control factors of the BTA drilling process. The control factor settings that yield the best-quality characteristic can be determined from these response graphs. By selecting those factors with higher S/N ratio values, the best hole roundness from BTA drilling is achieved at:

- Tool diameter $d = 26.40$ mm,
- Shaft length $\ell = 1200$ mm,
- Feed rate $\Delta z = 0.05$ mm/rev,
- Rotational speed $n = 390$ rpm,
- Day 1 machining.

Table 5. S/N ratio response table for roundness error

Symbol	Control factor	S/N ratio (dB) Level 1	S/N ratio (dB) Level 2	Level difference (dB)
A	Tool diameter	50.53	53.63	3.10
B	Shaft length	53.28	50.88	2.40
C	Feed rate	54.81	49.35	5.46
D	Rotational speed	54.06	50.09	3.97
N	Day of the week (noise)	52.17	51.99	0.18

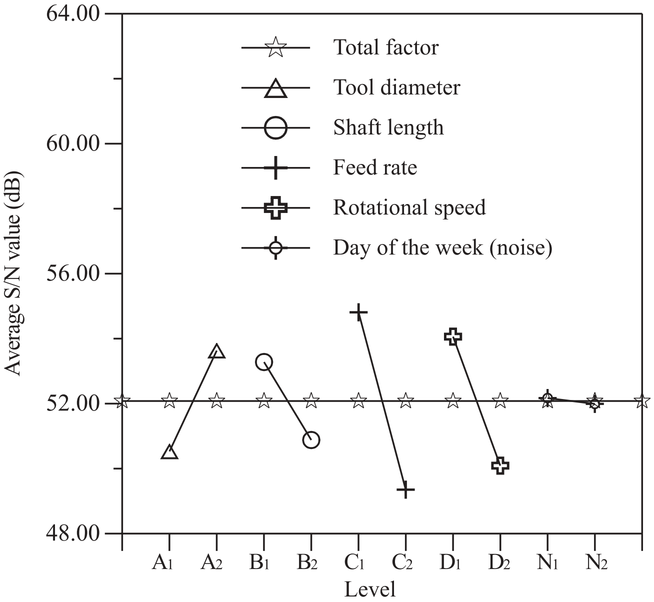


Fig. 3. Response graphs for hole roundness error

3.3 Analysis of variance

The purpose of the analysis of variance (ANOVA) is to determine the control factor that significantly affects the quality characteristic. Besides the significance of control factors, the significance of their interactions on the roundness error of the hole was studied as well. The interactions among control factors were between:

- Tool diameter and noise ($A \times N$),
- Shaft length and noise ($B \times N$),
- Feed rate and noise ($C \times N$),
- Rotational speed and noise ($D \times N$).

The percentage contribution of each process factor in the total sum of squares can be used to evaluate the importance of the process factor change on the performance characteristic. Additionally, the F value, named after Fisher [9], can be used to determine which process factors significantly affect the performance characteristic. Usually the change in the process factor significantly affects the performance characteristic when F is large.

The ANOVA is used to analyse the experimental data as follows [10]:

$$SS_T = \sum \eta_{ij}^2 - \frac{\left(\sum \eta_{ij}\right)^2}{16} \tag{4}$$

$$SS_P = \frac{\left(\sum \eta_{P_k}^2\right)^2}{8} - \frac{\left(\sum \eta_{ij}\right)^2}{16} \tag{5}$$

$$SS_E = SS_T - \sum SS_P \tag{6}$$

$$V_P = \frac{SS_P}{DF_P} \tag{7}$$

$$F_P = \frac{V_P}{V_e} \tag{8}$$

$$\varrho_P = \frac{SS_P - DF_P V_e}{SS_T}, \tag{9}$$

where SS_T is the total sum of squares; SS_P is the sum of squares of factor P ($P = A, B, C, D, N, A \times N, B \times N, C \times N$ and $D \times N$); SS_E is the sum of squares of error; η_{ij} is the η value of each experiment ($i = 1$ to 2, $j = 1$ to 8), as shown in Table 4; n_{P_k} is the η value of level k ($k = 1, 2$) of factor P; DF_P is the number of degrees of freedom of factor P; V_P is the mean square of factor P; F_P is the F value of factor P; V_e is the variance of pooled error (i.e., summed error); and ϱ_P is the percentage contribution of factor P.

Based on the S/N ratio values (Table 4) and using Eqs. 4–9, the ANOVA for the roundness error of the holes can be calculated as shown in Table 6. An estimate of the sum of squares for the pooled error can be obtained by pooling the sum of squares of factors with the lowest sum of squares – noise, interactions among the control factors, and error. The pooled error has

Table 6. ANOVA for roundness error (S/N analysis)

Factor (p)	Degrees of freedom (DF_P)	Sum of squares (SS_P)	Mean square (V_P)	F value (F_P)	Contribution (ϱ_P)
A	1	38.2542	38.2542	33.7249	14.50%
B	1	23.0880	23.0880	21.9537	8.58%
C	1	119.1372	119.1372	105.0315	46.09%
D	1	63.0436	63.0436	55.5793	24.18%
N	1	0.1190*			
$A \times N$	1	0.0210*			
$B \times N$	1	0.1332*			
$C \times N$	1	0.0812*			
$D \times N$	1	0.1521*			
Error	6	11.9709*			
Pooled error	Eq. 11	(12.4774)	(1.1343)	(17.0146)	(6.65%)
Total	15	256.0004		256.0004	100%

* Indicates the sum of squares added together to estimate the pooled error sum of squares in parentheses.

11 degrees of freedom and a sum of squares of 12.4774, as indicated in parentheses. Hence the pooled error variance is 1.1343. The F value can be found using the ratio of mean square of a factor to variance of pooled error. It can be seen from the F value result that the significant factors are the control factors in the order C (feed rate), D (rotational speed), A (tool diameter) and B (shaft length). Furthermore, the feed rate is the most significant drilling process since it contributes a greater percentage than all the other control factors. The conclusions in Tables 5 and 6 are consistent with the multiple performance characteristics.

3.4 Determination of optimal machining conditions

Tables 5 and 6 show that control factors have different influences upon hole roundness in the BTA drilling process. Optimal machining conditions in terms of these control factors can be very easily determined from the S/N ratio response graphs in Fig. 3. Best hole roundness values are obtained at higher S/N ratios. Table 7 presents optimal machining conditions for a drilling workpiece. It is obvious that the noise has only weak influence on the machining quality, which shows the robustness of the BTA drilling process.

Equation 10 determines the S/N ratio at optimal settings of the main control factors. We can derive the expression for roundness error Eq. 11 from Eq. 1 and calculate the roundness error (R_{cal}) at optimal machining conditions:

$$\begin{aligned}\eta_{cal} &= \bar{\eta} + \left(\bar{A}_2 - \bar{\eta}\right) + \left(\bar{B}_1 - \bar{\eta}\right) + \left(\bar{C}_1 - \bar{\eta}\right) + \left(\bar{D}_1 - \bar{\eta}\right)\\ &= \bar{A}_2 + \bar{B}_1 + \bar{C}_1 + \bar{D}_1 - 3\bar{\eta}\\ &= 53.63 + 53.28 + 54.81 + 54.06 - 3 \times 52.08\\ &= 59.54\,, \end{aligned} \tag{10}$$

$$R_{cal} = 10^{-\eta_{cal}/20} = 10^{-59.54/20} = 0.0011\ \text{mm}\,, \tag{11}$$

where η_{cal} is the S/N ratio at optimal machining conditions, $\bar{\eta}$ is the average S/N ratio of all control factors, $\bar{A}_2$ is the average S/N ratio when factor A (tool diameter) is at level 2, $\bar{B}_1$ is the average S/N ratio when factor B (shaft length) is at level 1, $\bar{C}_1$ is the average S/N ratio when factor C (feed rate) is at level 1, and $\bar{D}_1$ is the average S/N ratio when factor D (rotational speed) is at level 1. Comparing Eq. 10 with Table 4, and Eq. 11 with Table 3 reveals that the optimal combination of $A_2B_1C_1D_1N_1$ yielded the highest S/N ratio and the best hole quality.

Table 7. Optimal settings of control factors

Control factor	Notation	Setting
Tool diameter, d (mm)	A_2	26.40
Shaft length, ℓ (mm)	B_1	1200
Feed rate, Δz (mm/rev)	C_1	0.05
Rotational speed, n (rpm)	D_1	390
Day of the week (noise)	N_1	Day 1

3.5 Confirmatory test

A confirmatory test was performed after the optimal control factor settings were determined. The confirmatory test is a repetition of the experiment in BTA machining with the control factors set at optimal settings to achieve the predicted quality characteristics. Two trials at the optimal control factor settings were made in the confirmation test. The results of the confirmatory test are presented in Table 8. The table shows that S/N ratios of 57.36 and 57.70 dB correspond to average roundness errors of 0.0014 and 0.0013 mm, respectively. Furthermore, the CI value of 5% confi-

Table 8. Confirmatory test results

Trial no.	Roundness error, R (mm)				Average roundness error R_{ver} (mm)	S/N ratios η_{ver} (dB)
	50 mm	100 mm	150 mm	200 mm		
1	0.0015	0.0014	0.0012	0.0013	0.0014	57.36
2	0.0014	0.0013	0.0013	0.0012	0.0013	57.70

Table 9. Compare confirmatory test results and calculated value

Trial no.	Confirmatory test results		Calculated values		Difference	
	R_{ver} (mm)	η_{ver} (dB)	R_{cal} (mm)	η_{cal} (dB)	$\lvert R_{ver} - R_{cal} \rvert$	$\lvert \eta_{ver} - \eta_{cal} \rvert$
1	0.0014	57.36	0.0011	59.54	0.0003	2.18
2	0.0013	57.70	0.0011	59.54	0.0002	1.84

dence band with the confirmatory test trial number is calculated according to [7]

$$CI = \sqrt{F_{0.05;1;v_e} \times V_e \times \left(\frac{1}{n_{eff}} + \frac{1}{n_{ver}} \right)} = \sqrt{4.84 \times 1.1343 \times \left(\frac{5}{8} + \frac{1}{2} \right)} = 2.49 \tag{12}$$

$$n_{eff} = \frac{n_{tol}}{1+v} = \frac{8}{1+4} = \frac{8}{5}, \tag{13}$$

where $F_{0.05;1;v_e}$ is the F value for 95% confidence [10], v_e is the degrees of freedom for pooled error, V_e is the variance of pooled error, n_{tol} is the total trial number, v is the total main factor degrees of freedom, and n_{ver} is the confirmatory test trial number. Table 9 shows some differences between the values obtained in the confirmatory test (Table 8) and the calculated values (Eq. 10) of the S/N ratios, but differences of 2.18 and 1.84 dB are under a 5% confidence band value of 2.49 dB, and thus at a 95% confidence level. Hence the optimal control factor settings were confirmed and further experiments could be performed or response roundness methods applied.

3.6 Discussion

In the factor space explored, the feed rate is the most significant process variable affecting hole roundness. The lower feed rate of 0.05 mm/rev was preferred to the higher feed rate of 0.1 mm/rev. A higher feed rate creates a larger chip and the tool bears a greater cutting force [11], producing a larger deflection of the tool shaft than that obtained at a lower feed rate. High rotational speed increases productivity; however, a low rotational speed of 390 rpm was preferred in the experiments because the tool shaft produces vibrations at higher speeds [1]. The tool diameter of 26.40 mm was preferred over the smaller diameter of 18.91 mm because the tool shaft with the larger diameter is stiffer than the one with the smaller diameter [12]. The 1200-mm-long shaft was preferred to the 1600-mm-long shaft because a shorter shaft is stiffer [12] and thus produces a smaller deflection.

4 Conclusions

Hole roundness in BTA deep-hole drilling was analysed by Taguchi methods. The hierarchy of process variables affecting roundness was established, and optimal cutting conditions for obtaining a hole with the desired roundness with a minimal number of experimental runs were determined. Optimal cutting conditions were confirmed with a verification experiment.

The response table of the S/N ratios and the ANOVA analysis for all five control factors shows a very strong influence of feed rate (C), a strong influence of rotational speed (D) and tool diameter (A), a moderate influence of shaft length (B) and no or little influence of noise (N) on the roundness of the hole formed in BTA drilling. The optimal control settings of $A_2B_1C_1D_1N_1$ were found to yield the highest S/N ratios and optimal hole quality. At these optimal settings, the confirmatory test returned a roundness error within the 95% confidence interval.

Verifying sufficient roundness is especially important in two situations: when the machining phase represents an important portion of the production cost of a product and when a small number of very expensive workpieces are being machined. This study contributes to research in BTA drilling and describes a robust approach to this process which offers a basis for further cost-effective machining processes.

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Appendix A

Experimental equipment:

1. Lathe
   SAN SHING SK26120 HEAVY-DUTY PRECISION LATHE
   BTA drilling system (Fig. 1)
2. BTA drilling
   (a) Tool head: SANDVIK 420.6 series
   (b) Tool shaft
      Type: SANDVIK 420.5-800-2
      - Tool head: 18.91 mm, internal and external diameters of tool shaft: 11.5 and 17 mm, respectively; shaft length: 1600 mm
      - Tool head: 26.40 mm; internal and external diameters of tool shaft: 14 and 22 mm, respectively; shaft length: 2600 mm

      Material: JIS SNCM 21
      Density ϱ: 7860 $\mathrm{kg/m^3}$
      Young's modulus E: 206×10^9 Pa
3. Cutting fluid
   Type: R32
   Density ϱ_f: 871 $\mathrm{kg/m^3}$
   Absolute viscosity μ: 0.383 $\mathrm{kg/m \cdot sec}$