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EVALUATION OF THE SURFACE ROUGHNESS AND GEOMETRIC ACCURACIES IN A DRILLING PROCESS USING THE TAGUCHI ANALYSIS

OCENA HRAPAVOSTI POVRŠINE IN GEOMETRIJSKE NATANČNOSTI POSTOPKA VRTANJA Z UPORABO TAGUCHIJEVE ANALIZE

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This paper presents an evaluation of the surface roughness and geometric accuracies in drilling operations performed using U-drills without a pilot hole. The surface roughness, perpendicularity and cylindricity were used as the response parameters for evaluating the effects of the feed rate, peripheral speed, hole diameter and hole depth. The performance characteristics were measured and various signal-noise ratios were calculated with the Taguchi method. An analysis of variance (ANOVA) was performed and the effects of the controlled factors at different levels were analyzed to identify the optimum drilling conditions for U-drills. The results of this study will allow an operator to select the optimum parameter values for U-drills to reduce the manufacturing costs.

Keywords: surface roughness, perpendicularity, cylindricity, U-drills, coated indexable insert drills, Taguchi method, optimization

Članek predstavlja oceno hrapavosti površine in geometrijske natančnosti operacije vrtanja, izvršene z U-svedrom brez vodilne izvrtine. Hrapavost površine, navpičnost in cilindričnost so bile uporabljene kot odgovarjajoči parametri za oceno odvzema, obodne hitrosti, premera in globine luknje. Izmerjene so bile značilnosti delovanja, razmerja signalov hrupa pa so bila izračunana z uporabo Taguchijeve metode. Izvršena je bila analiza variance (ANOVA) in analizirani kontrolni faktorji vpliva na različnih nivojih, da bi ugotovili optimalne razmere vrtanja za U-svedre. Rezultati te študije bodo omogočili operaterju, da bo izbral optimalne vrednosti parametrov za U-sveder in za zmanjšanje proizvodnih stroškov.

Ključne besede: hrapavost površine, pravokotnost, cilindričnost, U-svedri, prekriti indeksirani vložki svedrov, Taguchijeva metoda, optimizacija

1 INTRODUCTION

Drilling is usually the most efficient and economical method of cutting a hole in a solid metal and has a considerable economic importance because of its wide application in most of the manufactured components. It has been reported that drilling accounts for nearly 40 % of all the metal-removal operations in the aerospace and automobile industries.[1] Hence, achieving a required hole quality is important for the functional-behavior parts and the economics of drilling operations.

Drilling operations are not regarded as precision machining and, thus, subsequent operations are required to improve the accuracy levels. These finishing operations improve the surface finish significantly; however, eliminating the inaccuracies resulting from drilling operations is difficult.[2–5] Therefore, many researches were carried out to evaluate the surface roughness and accuracy of drilled holes. These researches were largely concentrated on finding the effects of cutting speed, feed rate, tool geometry, type of the material and rigidity of the machine tools, using twist drills.[6–10] Most of these researches were focused on the optimization of the parameters using the Taguchi method. However, little work has been reported on the effects of the hole depth and hole diameter on the quality of the holes obtained with U-drills.

The usual procedure for drilling large holes is that first a pilot hole is drilled to overcome the poor cutting of large drills. The hole quality is affected by several factors such as tool geometry, cutting speed, feed rate, workpiece material and rigidity of the machine tool.[11,12] The drill geometry is considered to be the most important factor affecting a drill performance. Hence, with the development of the tools featuring indexable inserts (commonly referred to as U-drills), the need for the preparatory and subsequent machining has changed drastically. Modern tools have led to the solid drilling being carried out in a single operation without any previous drilling of the centre and pilot holes, making the hole production more productive.[13]

This study aims to minimize and/or eliminate the subsequent operations needed after the drilling operations using U-drills. U-drills are generally used for roughing operations to reduce the machining time by cutting holes without any pilot drilling. Using the optimum feed rate is important in this type of drilling operations. The feeds that are too low may cause an unsatisfactory surface finish due to the swaging during the initial penetration of the tool into a workpiece. On the other hand, excessive cutting forces, due to high feeds, may cause poor tolerances and damage on a workpiece and tool holder because of the fracture on the tool inserts. This study aims to minimize and/or eliminate the subsequent operations needed after the drilling operations by optimizing the process parameters such as the cutting speed, feed rate, hole diameter and hole depth using the Taguchi method. A horizontal CNC machining center was used for the drilling tests. Medium-carbon steel was used as the workpiece material. The surface roughness, perpendicularity and cylindricity were selected as the performance characteristics. Then, the optimum process parameters for the best surface finish and hole accuracy were derived from the analysis of the results. The parameters having the major effects on the hole quality and the percentage contribution of these effects were analyzed and, finally, confirmation tests were carried out comparing these results with the experimental results.

2 EXPERIMENTAL DETAILS

2.1 Design of experiments

Designs of experiment techniques, specifically orthogonal arrays (OA), are employed in the Taguchi approach to systematically vary and test different levels of each of the control factors.[14] The commonly used orthogonal arrays include L_4, L_9, L_{12}, L_{18}, and L_{27} depending upon the number of the parameters to be studied and the levels for each factor. In this work, four parameters, namely A, B, C and D, at three levels were investigated. Therefore, the L_9 (3^4) orthogonal array, shown in **Table 1**, was employed for the design of the experiments.

Specific test characteristics for each experimental evaluation are identified according to the associated row of the L_9 orthogonal-array table. L_9 means that nine experiments have been performed to study the effects of four variables at three levels. The number of columns of an array in the table represents the maximum number of the parameters that can be studied using that array. The columns in an orthogonal array indicate the factor and its corresponding levels, and each row in the orthogonal array constitutes an experimental run performed at the given factor settings.

In this study, only a specific kind of workpiece material was considered, so the workpiece material had no effect on the variations of responses. Different diameters were considered for the desired holes using the tools with the same geometry and grade. All the experiments were performed on the same drilling machine, so the machine and the process had no effect on the variations of responses. The flank wear and crater wear were checked on the tools after every set of experiments due to their significant effects on the surface finish and cutting forces and no wear was detected on the cutting tools. Therefore, it is assumed that the chatter effect had no influence on the variations of responses.

The feed and cutting speed are two important process parameters for achieving the desired material-removal rate and productivity in drilling. The use of a better tool material with a higher strength and hot hardness and a better drill geometry design can enable a larger feed in drilling. The effect of the feed in drilling is an area that had not been studied extensively.[15] Therefore, the cutting speed and the feed rate were defined as the controlled factors. Additionally, the hole diameter and hole depth were considered as they represent the constraints in a drilling process in today's machining applications. The steps defined in **Figure 1** were followed when conducting the experiments and analyzing the results to investigate the effects of the process parameters on the surface roughness, perpendicularity and cylindricity.

A product array was used to test various combinations of the control-factor settings against all the combinations of the noise factors. Then, the mean response and the standard deviation were approximated for each run using the following equations:

$$y_{\text{ave}} = \frac{1}{n}\sum_{i=1}^{n} y_i \quad \text{is the mean response} \qquad (1)$$

Table 1: L_9 orthogonal array used for the design of the experiments and controlled factors with their levels
Tabela 1: Ortogonalna postavitev L_9, uporabljena za postavitev preiskav in kontrolnih faktorjev z njihovimi nivoji

Run # /trial #	Level	Factor A Hole diameter (mm)	Level	Factor B Hole depth (mm)	Level	Factor C Feed rate (mm/r)	Level	Factor D Cutting speed (m/min)
1	1	19	1	45	1	0.06	1	140
2	1	19	2	68	2	0.09	2	160
3	1	19	3	95	3	0.12	3	180
4	2	23	1	45	2	0.09	3	180
5	2	23	2	68	3	0.12	1	140
6	2	23	3	95	1	0.06	2	160
7	3	26	1	45	3	0.12	2	160
8	3	26	2	68	1	0.06	3	180
9	3	26	3	95	2	0.09	1	140

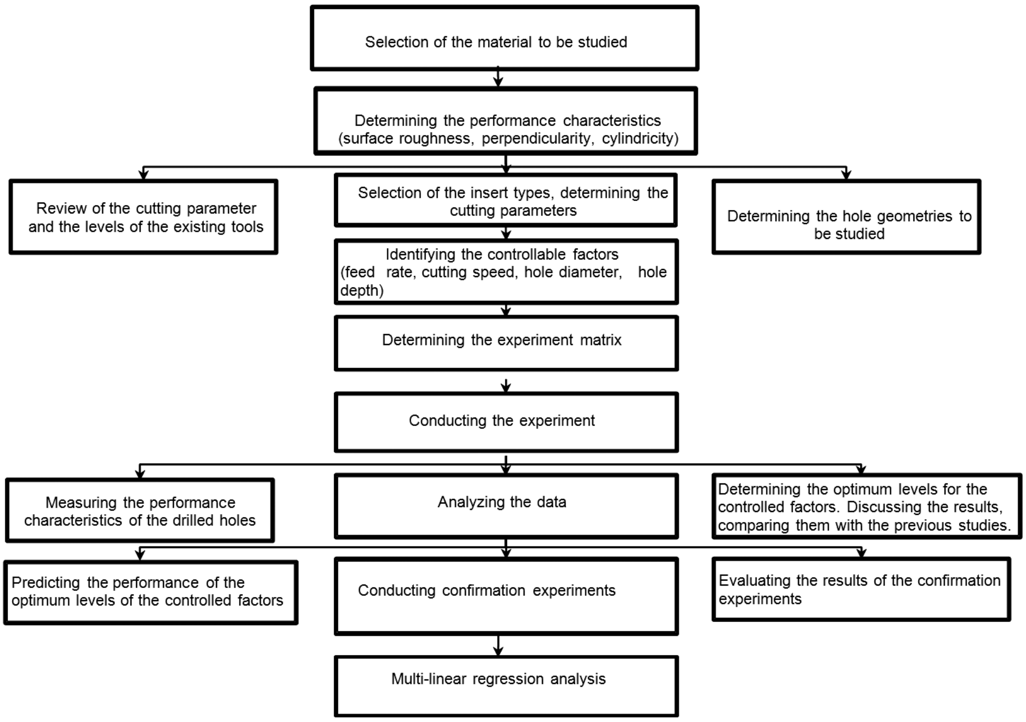

Figure 1: Flowchart of the Taguchi method employed in this study
Slika 1: Diagram Taguchijeve metode, uporabljene v tej študiji

$$S=\frac{1}{n}\sqrt{\sum_{i=1}^{n}\frac{(y_i-y_{\text{ave}})^2}{n-1}} \text{ is the standard deviation} \quad (2)$$

The preferred parameter settings were then determined through an analysis of the signal-to-noise (*S/N*) ratio. These *S/N* ratios were derived from the quadratic loss function and expressed with a decibel scale. After all of the *S/N* ratios were computed for each run of the experiment, a graphical approach was used to analyze the data. In the graphical approach, the *S/N* ratios and the average responses were plotted for all the factors against their levels. The graphs were then examined to select the factor level that best maximizes each *S/N* ratio. Finally, confirmation tests were conducted for the optimum setting parameters to verify that the defined performance was actually realized.

2.2 Workpiece material

In this study, hot-rolled low-alloyed medium-carbon steel of 207 HB was used as the workpiece material. This material with the chemical composition given in **Table 2** is modified from C35 and used in the automobile industry. The workpieces were 250 mm in length with a square cross-section of 80 mm × 80 mm.

Table 2: Chemical composition of the workpiece material in mass fractions (*w*/%)
Tabela 2: Kemijska sestava materiala obdelovanca v masnih deležih (*w*/%)

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Sn
0.37	0.57	0.97	0.013	0.055	0.16	0.01	0.12	0.017	0.22	0.014

2.3 Cutting tools

The U-drilling tools, shown in **Figure 2**, were used in the experiments. A U-drilling tool has two internal coolant flutes and indexable central and peripheral inserts. The central inserts are made of 1044-grade, fine-grained, cemented carbide PVD coated with a bronze-colored TiAlN layer 3 μm. The peripheral inserts were of grade 4024. They had a cemented carbide substrate coated with a MT-CVD layer of TiCN ensuring the abrasive wear resistance, followed by a layer of Al_2O_3 providing a high-temperature protection.

2.4 Experimental setup

An OKUMA MA-500HB SPACE CENTER, a horizontal CNC machining center with an OSP E100M controller, was used for conducting the experiments in this

Figure 2: a) U-drill tool, b) central insert, c) peripheral insert
Slika 2: a) U-vrtalno orodje, b) centralni vložek, c) obodni vložek

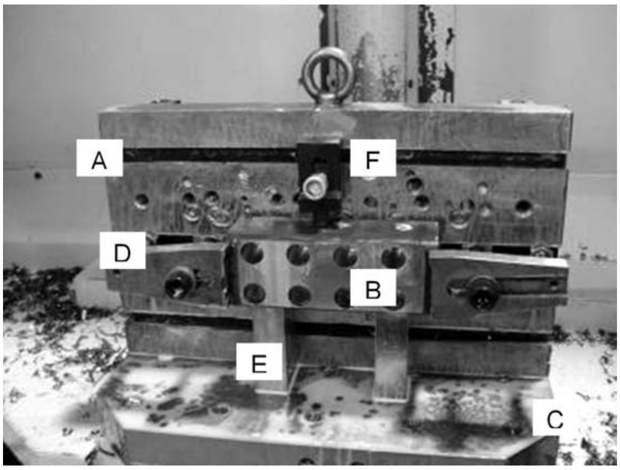

Figure 3: Fixture used during the test
Slika 3: Pritrditev, uporabljena pri preizkusu

study. During the tests, the machine spindle torque was limited by the controller to about 25 % of the maximum spindle torque of a usual application in a factory during production.

The initial start-up checks were performed before the drilling in order to minimize and eliminate the sources of variation and increase the reliability of the results. The linear positioning accuracy of the machine was checked according to ISO 230-1 at three axes and found to be about 3 µm. The repeatability of the positioning accuracy of the machine at three axes was found to be about 1 µm. The spindle speed was checked with a SCHENCK VIBRO BALANCER 42 and no deviation was detected. A torque meter was used to tighten the workpiece repeatably by applying a 220 N m torque. The radial run-out of the drilling tool was checked before every run of the experiments. The maximum total run-out of the drilling tool was detected as 0.05 mm. The workpiece surface was cleaned by milling to eliminate the effect of an angular deviation between the tool and the workpiece before the drilling process.

The fixture used during the tests is shown in **Figure 3**. The fixture consists of a support console (A), a workpiece (B), a pallet (C), the fixing arms (D), the lower supporting blocks (E) and the upper adjustable supporting blocks (F). The rear side of the workpiece was machined on a conventional milling machine before the drilling operations to eliminate the adverse effects of the tightening forces of the fixing arms.

2.5 Perpendicularity and cylindricity measurements

A CNC controlled coordinate measuring machine (CMM) was used to measure the perpendicularity and cylindricity of the holes during the experiments. The machine was ZEISS ACCURA CMM with a measuring range of 900 mm × 1500 mm × 700 mm. The machine was equipped with a multi-sensor rack for automated measuring without any manual changing of the probes for different purposes, having a passive scanning option. The linear measuring uncertainty of CMM was (2.2 + (*L*/300)) µm and the form uncertainty of the roundness was 1.7 µm during the scanning with a VAST XXT scanning probe. During the experiments, the linear and scanning uncertainties of the machine were verified with the linear and round standard gauge blocks.

2.6 Surface-roughness measurements

A stylus-contact-type device, MITUTOYO SJ 301 surface roughness tester, was used to measure the surface roughness of the holes during the experiments. The roughness tests were carried out according to DIN 1990. The device was verified before the measurements using a standard roughness specimen. The Gauss filter was used while measuring the P profile. The Ra average roughness parameter was selected as the output parameter to define the geometric irregularities of the surfaces drilled at different conditions. The values of 0.8 mm and 4.0 mm were selected for the cut-off and evaluated profile lengths, respectively. Five cut-off lengths were scanned with a measuring speed of 5 mm/s and three of them were filtered.

3 RESULTS AND DISCUSSIONS

Ten holes were drilled in a single operation without any previous drilling of the centre or the pilot holes on the experiment samples for each experimental run. Then, the effects of the process parameters on the three performance characteristics – the surface roughness, the perpendicularity and the cylindricity – were analyzed using the results of the *S/N* ratios and ANOVA. The results of the experiments performed at different levels of each factor with the corresponding *S/N* ratios and the total variations and standard deviations determined for the performance characteristics are given in **Tables 3** and **4**, respectively.

3.1 Data analysis based on the S/N ratios and ANOVA

3.1.1 Surface roughness

The average *S/N* ratio of the controlled factors affecting the surface roughness were determined and given in **Table 5** and **Figure 4**. The optimum combination of the hole diameter, hole depth, feed rate and cutting speed, giving the best performance characteristics, was determined as A3 (a 26 mm hole diameter), B1 (a 45 mm hole depth), C1 (a 0.06 mm/r feed rate) and D3 (a 180 m/min cutting speed) using the distribution of the average *S/N* ratios shown in **Figure 4**.

The analysis of variance for different drilling modes, given in **Table 6**, shows that the most important variable affecting the surface roughness is the hole diameter with a percentage contribution of 70.64 %. The maximum deviation in the surface-roughness value was detected when the hole diameter was changed within the range of 19 mm and 26 mm. This was due to the changes in the

Table 3: Average surface-performance-characteristic values obtained for different configurations and the *S/N* ratios estimated for each run
Tabela 3: Povprečne vrednosti značilnosti vedenja površine pri različnih postavitvah in *S/N*-razmerjih, dobljenih pri vsaki ponovitvi

Run #	Average surface roughness (µm)	*S/N* ratio surface roughness (dB)	Average perpendicularity (mm)	*S/N* ratio perpendicularity (dB)	Average cylindricity (mm)	*S/N* ratio cylindricity (dB)
1	1.21	–1.693	0.0061	43.528	0.0325	29.6196
2	1.44	–3.270	0.0106	38.877	0.0727	22.5651
3	1.80	–5.279	0.0182	33.862	0.0479	26.3535
4	2.40	–6.578	0.0085	40.082	0.0278	31.0535
5	2.62	–10.174	0.0150	35.242	0.0394	18.5163
6	2.58	–5.319	0.0113	35.749	0.0265	25.0493
7	1.21	–1.748	0.0095	39.816	0.0261	31.3278
8	0.80	1.779	0.0121	37.719	0.0483	25.9372
9	1.26	–2.037	0.0259	30.409	0.0485	25.8253
S/N total		–34.319		335.283		236.248
S/N average		–3.813		37.254		26.250

Table 4: Total variations and standard deviations determined for the performance characteristics
Tabela 4: Skupni odmiki in standardna deviacija, določena pri značilni učinkovitosti

Run #	Ave. surface roughness (µm)	Total var. R_a (µm)	St. dev. R_a (µm)	Ave. perp. (mm)	Total var. perp. (mm)	St. dev. perp. (mm)	Ave. cyl. (mm)	Total var. cyl. (mm)	St. dev. cyl. (mm)
1	1.21	± 0.215	0.149	0.006 1	± 0.004	0.003	0.0325	± 0.011	0.006
2	1.44	± 0.350	0.214	0.010 6	± 0.007	0.004	0.0727	± 0.028	0.017
3	1.80	± 0.435	0.373	0.018 2	± 0.013	0.009	0.0479	± 0.008	0.004
4	2.40	± 0.565	0.320	0.008 5	± 0.009	0.005	0.0278	± 0.005	0.004
5	2.62	± 0.520	0.451	0.015 0	± 0.012	0.008	0.0394	± 0.005	0.004
6	2.58	± 0.39	0.237	0.011 3	± 0.012	0.009	0.0265	± 0.005	0.003
7	1.21	± 0.230	0.164	0.009 5	± 0.007	0.004	0.0261	± 0.012	0.008
8	0.80	± 0.225	0.152	0.012 1	± 0.008	0.005	0.0483	± 0.023	0.015
9	1.26	± 0.01	0.061	0.025 9	± 0.023	0.016	0.0485	± 0.025	0.017

power requirement for drilling different sizes of the holes. The feed rate also had a significant effect on the surface roughness with a percentage contribution of 24.97 %. This means that these two factors must be considered first when optimizing the process parameters to improve the surface finish in drilling processes.

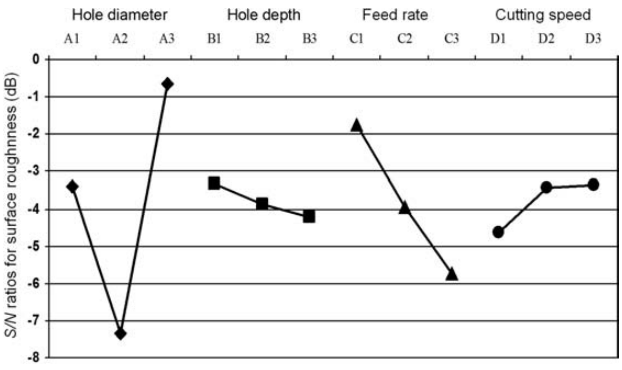

Figure 4: *S/N* response graph of the surface roughness
Slika 4: Graf *S/N*-odgovorov na hrapavost površine

Table 5: *S/N* response table for the surface roughness
Tabela 5: Tabela *S/N*-odgovorov pri hrapavosti površine

Factor	Mean *S/N* ratio (dB)			
	Level 1	Level 2	Level 3	Difference N
A: hole diameter	–3.414	–7.36	–0.669	6.689
B: hole depth	–3.340	–3.888	–4.212	0.872
C: feed rate	–1.744	–3.962	–5.734	3.990
D: cutting speed	–4.635	–3.446	–3.359	1.275

Table 6: Analysis of variance for the surface roughness
Tabela 6: Analiza variance za hrapavost površine

Source of variation		Degree of freedom	Sum of squares	Mean square	Contribution %
A	hole diameter	2	67.8224	33.911	70.64
B	hole depth	2	1.1657	0.5828	1.21
C	feed rate	2	23.9766	11.988	24.97
D	cutting speed	2	3.0485	1.5243	3.18
Total		8	96.013		100

With the optimum levels of the controlled factors, the predicted *S/N* ratio for the surface roughness to be used in the verification of the experiment was found using the following equation:

$\mu_{A3,B1,C1,D3}$ = [(–1.748 + 1.779 + (–2.037)) /3 + (–1.693 + (–6.578) +(–1.748)) /3 + (–1.693 + (–5.319) + 1.779) /3 + (–5.279 + (–6.578) + 1.779) /3] – (3 – 3.813) = 2.3279979 dB

Using the data given in **Table 5** and **Figure 4**, a confirmation test was carried out. Ten holes were drilled on the experiment specimen using the determined parameters. The *S/N* ratio of the confirmation test was calculated as:

$\mu_{A3,B1,C1,D3} = -0.71$ dB.

The predicted *S/N* ratio was 2.327 dB, but when compared with the *S/N* ratios given in **Table 3**, a significant improvement was employed. The mean *S/N* ratio of the experiments was –3.813 dB. Hence, the improvement ratio of 81.4 % was found when considering the mean value of the *S/N* ratio.

A multi-linear regression analysis was carried out for the data range given in **Table 1** to model the relationship between the factors and the performance measure. This equation gives the expected value of the surface roughness for any combination of the feed rate, cutting speed and hole diameter. The regression equation obtained with the coefficient of determination, $R^2 = 0.9207$, was as follows:

$$R_a = 25.40\,f - 0.011\,V_c + 0.049\,D \tag{3}$$

Using the range of the selected parameters of f = 0.06–0.12 mm/r, V_c = 140–180 m/min and D = 19–26 mm, the range of the R_a values can be computed using equation 3:

R_a = 25.40 (0.06–0.12) – 0.011 (140–180) + 0.049 (19–26)

R_a = (1.524–3.048) – (1.54–1.98) + (0.931–1.274)

R_a = (0.915–2.342)

From the absolute values for the selected parameters, the importance coefficients of the parameters for the surface roughness can be calculated as follows:

IC_f /% = [(1.524 / 3.995), (3.048 / 6.302)] = (38.15–48.37)

IC_{Vc}/% = [(1.54 / 3.995), (1.98 / 6.302)] = (31.42–38.55)

IC_D /% = [(0.931 / 3.995), (1.274 / 6.302)] = (23.30–20.21)

3.1.2 Perpendicularity

The average *S/N* ratios of the controlled factors affecting the perpendicularity were determined and the results are given in **Table 7**. The average *S/N* ratios for the perpendicularity are shown in **Figure 5**. It is evident from this figure that the optimum conditions are A1 (a 19 mm hole diameter), B1 (a 45 mm hole depth), C1 (a 0.06 mm/r feed rate) and D2 (a 160 m/min cutting speed).

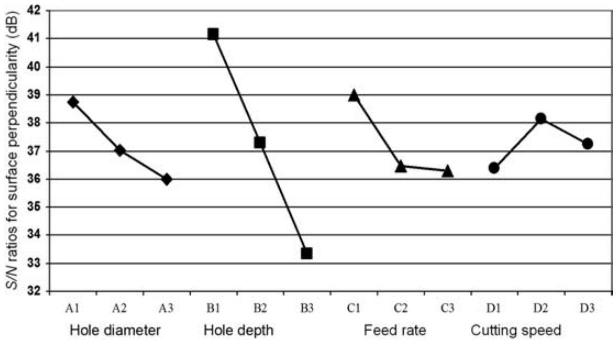

Figure 5: *S/N* response graph of the perpendicularity
Slika 5: Graf odgovora *S/N* na navpičnost

Table 7: *S/N* response table for the perpendicularity
Tabela 7: Tabela odgovora *S/N* na navpičnost

		Mean *S/N* ratio (dB)			
Symbol	Factor	Level 1	Level 2	Level 3	Difference n
A	Hole diameter	38.755	37.02	35.981	2.774
B	Hole depth	41.142	37.279	33.340	7.802
C	Feed rate	38.999	36.456	36.307	2.692
D	Cutting speed	36.393	38.148	37.221	1.755

With the optimum levels of the controlled factors, the predicted *S/N* ratio for the perpendicularity was calculated from the following equation:

$\mu_{A1,B1,C1,D2}$ = [(43.528 + 38.877 + 33.682)/3 + (43.528 + 40.082 + 39.816)/3 + (43,528 + 35.749 + 37.719)/3 + (38.877 + 35.749 + 39.816)/3] – (3 × 37.254) = 45.282494 dB

Table 8: Analysis of variance for the perpendicularity
Tabela 8: Analiza variance za navpičnost

Source of variation		Degree of freedom	Sum of squares	Mean square	Contribution %
A	hole diameter	2	11.780	5.890	9.70
B	hole depth	2	91.307	45.653	75.18
C	feed rate	2	13.756	6.868	11.31
D	cutting speed	2	4.624	2.312	3.81
Total		8	121.446		100

The analysis of variance (**Table 8**) show that the most important variable affecting the perpendicularity is the hole depth with a percentage contribution of 75.18 %. The maximum deviation in the perpendicularity value was detected when the hole depth increased in the range of 45–95 mm. This could be due to an excessive deflection of the tool and a difficulty in removing the chips from the cutting zone as the hole depth was increased. Hence, the chip control should be considered carefully when the chip-removing distance increases. The hole diameter and the feed rate have significant effects on the perpendicularity with percentage contributions of 9.70 % and 11.31 %, respectively. The contribution of the cutting speed to the perpendicularity was found to be 3.81 %. Its effect is not significant compared to the other parameters studied in this work. This means that three of these four factors must be considered when an optimization is planned for the range of the parameters given in **Table 1**. The results of the analysis of variance indicate that the control of the force acting on the tool and chip becomes an important factor when the chip-removing distance increases.

Using the data obtained from **Table 7** and **Figure 5** a confirmation test was carried out. Ten holes were drilled on the experiment specimen using the selected parameters. The *S/N* ratio of the confirmation test was calculated as:

$\mu_{A1,B1,C1,D2}$ = 31.90 dB

The predicted *S/N* ratio was 45.282 dB. The *S/N* ratio of the confirmation test for the cylindricity was lower than the predicted value. Although the predicted *S/N* ratio value was not reached, the mean perpendicularity value (0.0240 mm) obtained under the optimum conditions shows that a 52 % improvement was achieved compared to the target perpendicularity-deviation value (0.05 mm) planned for the initial conditions of this work.

3.1.3 Cylindricity

The average *S/N* ratio of the controlled factors affecting the cylindricity were determined and given in **Table 9** and **Figure 6**. As seen in **Table 9** and **Figure 6**, the controlled factors at the levels of A3 (a 26 mm hole diameter), B1 (a 45 mm hole depth), C1 (a 0.06 mm/r feed rate) and D3 (a 180 m/min cutting speed) give the optimum performance characteristics when the *S/N* analysis is used. With the optimum levels of the controlled factors the predicted *S/N* ratio for the cylindricity was calculated using the following equation:

$\mu_{A3,B1,C1,D3}$ = [(31.328 + 25.937 + 25.825)/3 + (29.620 + 31.054 + 31.328)/3 + (29.620 + 25.049 + 25.937)/3 + (26.354 + 31.054 + 25.937)/3] – (3 · 26.25) = 34.265 dB

A confirmation test was carried out using the data given in **Table 9** and **Figure 6**. Ten holes were drilled on the experiment specimen with the selected parameters for the optimum performance. The *S/N* ratio of the confirmation test was calculated as $\mu_{A3,B1,C1,D3}$ = 34.720 dB.

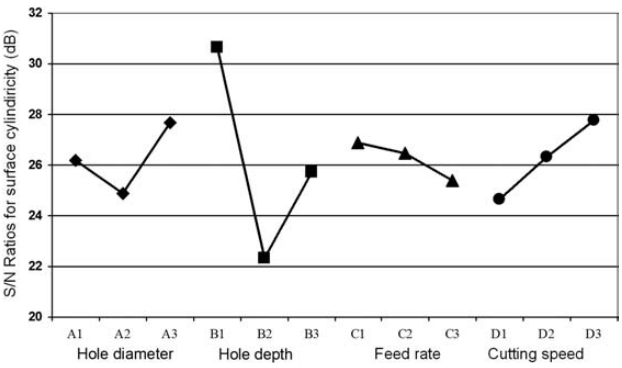

Figure 6: *S/N* response graph of the cylindricity
Slika 6: Graf odgovora *S/N* na cilindričnost

Table 9: *S/N* response table for the cylindricity
Tabela 9: Tabela odgovora *S/N* na cilindričnost

Symbol	Factor	Mean *S/N* ratio (dB)			
		Level 1	Level 2	Level 3	Difference n
A	Hole diameter	26.179	24.87	27.697	2.824
B	Hole depth	30.667	22.340	25.743	8.327
C	Feed rate	26.869	26.481	25.399	1.469
D	Cutting speed	24.654	26.314	27.781	3.128

The predicted *S/N* ratio was 34.265 dB. The *S/N* ratio of the confirmation test for the cylindricity was higher than the predicted value, but the predicted *S/N* ratio value was almost reached. The improvement ratio was 40 % when the mean *S/N* ratio of 26.520 dB was considered.

The analysis of variance for the cylindricity, given in **Table 10**, shows that the most important variable affecting the cylindricity is the hole depth with a percentage contribution of 77.72 %. After changing the hole depth in the range from 45 mm to 95 mm, the maximum deviation in the cylindricity value was detected. This can be explained with the fact that the tool deflection increases with the hole depth in drilling. Also, this fact might be a reason for the change in the chip-removing capability. The chip control becomes an important factor when the chip-removing distance increases. The hole diameter and the cutting speed also have significant effects on the cylindricity with the percentage contributions of 8.85 % and 10.86 %. This can be explained with the fact that the power requirement changes during drilling with a change in the hole diameter. In solid drilling, the depth of a cut equals half the diameter of a drilled hole. The feed rate had an insignificant effect on the cylindricity with a percentage contribution of 2.57 % under the conditions of these experiments.

Table 10: Analysis of variance for the cylindricity
Tabela 10: Analiza variance na cilindričnost

Source of variation		Degree of freedom	Sum of squares	Mean square	Contribution %
A	hole diameter	2	11.982	5.9912	8.85
B	hole depth	2	105.176	52.588	77.72
C	feed rate	2	3.480	1.7402	2.57
D	cutting speed	2	14.692	7.346	10.86
Total		8	135.331		100

Nearly the same cylindricity values were obtained for the cutting-speed values of 140 m/min and 160 m/min. On the basis of these results, the interaction between the feed rate and the cutting speed has to be further investigated in future studies. This can be seen from the calculated R^2 value of the most suitable formulation for the cylindricity under the given conditions of this experiment. The equation is as follows:

$$Cylindricity = 0.3289\,f + 0.00016\,V_c - 0.0016\,D \qquad (4)$$

R^2 = 0.7258

Using the selected parameters of f = 0.06–0.12 mm/r, V_c = 140–180 m/min and D = 19–26 mm, the range of the cylindricity values can be computed using equation 4:

$Cylindricity$ = 0.3289(0.06–0.12) + 0.00016(140–180) – 0.0016(19–26)

Cylindricity = (0.0197–0.0395) + (0.0224–0.0288) – (0.0304–0.0416)

Cylindricity = (0.0117–0.0267)

From the absolute values of the selected parameters, the importance coefficients of the parameters for the cylindricity can be calculated as follows:

$IC_f/\%$ = [(0.0197 / 0.0725), (0.0395 / 0.1099)] = (27.17–35.94)

$IC_{Vc}/\%$ = [(0.0224 / 0.0725), (0.0288 / 0.1099)] = (26.21–30.90)

$IC_D/\%$ = [(0.0304 / 0.0725), (0.0416 / 0.1099)] = (37.85–41.93)

4 CONCLUSIONS

In this study, it has been shown that the surface roughness, the perpendicularity and the cylindricity of drilled holes can be improved significantly when the target values were considered and compared at the design stage. Within the limits of the variables employed in the present experiments, the following conclusions can be drawn on the basis of the design planned with an L_9 (3^4) orthogonal array, using the Taguchi method for the solid drilling carried out with a single operation without any previous drilling of the centre or the pilot holes.

The experimental results indicated that the hole diameter and the feed rate have significant effects on the surface roughness. This shows that one of the important sources of the variation in the surface roughness is the hole diameter, as the power requirement changes during drilling when the hole diameter is changed.

The hole diameter and feed rate have significant effects on the perpendicularity with the percentage contributions of 9.70 % and 11.31 %. However, the most important variable affecting the perpendicularity was the hole depth with a percentage contribution of 75.18 %. After a change in the hole depth in the range from 45 mm to 95 mm, the maximum deviation in the perpendicularity was detected.

The percentage contributions of the hole diameter, the cutting speed and the feed rate to the cylindricity were found to be 8.85 %, 10.86 % and 2.57 %, respectively. However, the most important variable affecting the cylindricity was the hole depth with a contribution of 77.72 %. After a change in the hole depth in the range from 45 mm to 95 mm, the maximum deviation in the cylindricity was detected. The results show that the chip control should be carefully considered when the chip-removing distance increases.

The selected parameters (C1 and D3) for the minimum variation of the performance characteristics of the surface roughness, perpendicularity and cylindricity were used for drilling a hole with a 23 mm diameter and 100 mm depth on the same material and a 33.6 % reduction in the machining time was obtained compared to the usual drilling method. This test confirmed that with the optimum parameter combination selected with the Taguchi design, the desired performance characteristics can be achieved in actual drilling conditions.

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