



Optimization of Drilling Parameters for Improved Surface Quality Using Taguchi Method

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Abstract

Surface quality in drilling is strongly influenced by machining parameters, and inappropriate parameter selection can produce rough hole surfaces, excessive thrust, tool wear, and dimensional errors. This methodology paper presents a Taguchi-based experimental framework for optimizing drilling parameters with average surface roughness (Ra) as the primary quality response. A three-factor, three-level L9 orthogonal array is formulated using spindle speed, feed rate, and drill point angle. Each trial is repeated three times, and the results are analyzed using the smaller-is-better signal-to-noise (S/N) ratio, response means, and analysis of variance (ANOVA). A representative dataset is included to demonstrate the complete statistical workflow without claiming unperformed laboratory measurements. The illustrative analysis identifies feed rate as the dominant factor, followed by spindle speed and point angle. The predicted optimal combination is 1400 rpm spindle speed, 0.05 mm/rev feed, and 118-degree point angle. A confirmation result near 0.78 micrometre Ra would represent an improvement of approximately 45% relative to a central-setting condition. The proposed methodology provides a compact, reproducible procedure that can be applied to aluminium alloys, steels, and other engineering materials after suitable adjustment of parameter ranges.

Introduction

Drilling is one of the most frequently used hole-making operations in manufacturing, yet the quality of a drilled surface depends on coupled effects of cutting conditions, drill geometry, tool condition, work material, and machine rigidity. Average surface roughness, Ra, is particularly important because it influences fit, friction, fatigue initiation, sealing performance, and the need for secondary operations. Selecting drilling parameters only from handbooks or operator experience may therefore lead to inconsistent surface integrity, especially when production conditions vary.

Design of experiments offers a systematic alternative to one-factor-at-a-time trials. The

Taguchi method is attractive because orthogonal arrays reduce the number of experiments while still allowing the main effects of multiple factors to be estimated. Earlier drilling research has shown that Taguchi analysis can be used to minimize roughness in CNC drilling [3], identify the influence of coated tools and feed in stainless-steel drilling [6,7], and extend optimization to multiple responses such as roughness, thrust force, delamination, and burr formation [1,4,5]. These findings motivate a structured methodology focused specifically on surface quality.

Literature Review

Huang and Lin [1] applied a grey-Taguchi approach to drilling aluminium alloy 6061 and demonstrated that tool coating, spindle speed, and feed could be optimized when several performance measures, including surface roughness, tool life, and burr height, were considered simultaneously. Their study established the usefulness of combining Taguchi design with multi-response decision methods when surface finish is not the only quality requirement.

Tsao and Hocheng [2] evaluated thrust force and surface roughness in drilling composite material using Taguchi analysis together with a neural-network model. Their results emphasized that feed and spindle speed materially affect the drilled-surface condition. Zhang and Chen [3] later used Taguchi design for CNC drilling surface roughness and considered feed rate, spindle speed, peck rate, and tool type as control factors. Their confirmation experiments showed that a statistically selected parameter combination could produce the desired roughness more reliably than ad-hoc parameter selection.

Kuram et al. [4] investigated drilling AISI 304 using vegetable-based and commercial cutting fluids and used an L9 design with ANOVA to evaluate speed, feed, and drilling depth. Palanikumar [5] used Taguchi design with grey relational analysis in GFRP drilling, optimizing

roughness together with thrust force and delamination; feed rate was reported as more influential than spindle speed for the combined performance index. These studies show that the importance of individual factors depends on material, lubrication, and quality response, reinforcing the need for material-specific confirmation tests.

For stainless steels, Cicek, Kivak, and Samtas [6] used Taguchi analysis to optimize surface roughness and roundness in AISI 316 drilling, while Kivak, Samtas, and Cicek [7] evaluated uncoated and PVD-coated HSS drills and found tool condition and feed to be important for roughness and thrust force. Siddiquee et al. [8] optimized deep drilling of AISI 321 with an L18 array and ANOVA, reporting significant contributions from speed, cutting fluid, feed, and hole depth. Motorcu, Kus, and Durgun [9] demonstrated that point angle, feed, cutting speed, and tool type all contribute to Ra in Waspaloy drilling. Neseli [10] further showed how Taguchi and ANOVA can rank speed, feed, and drill geometry effects in drilling AISI 1040 steel. Finally, Parida, Routara, and Bhuyan [11] combined Taguchi and response-surface methodology for GFRP surface roughness in 2015. Collectively, literature up to 2015 supports a methodology that integrates orthogonal-array design, S/N analysis, ANOVA, and confirmation testing rather than relying on a single statistical indicator.

Table 1. Summary of Previous Studies on Drilling Parameter Optimization and Surface Roughness

Study	Material / design	Key factors	Main relevance
[3] Zhang & Chen, 2009	CNC drilling; Taguchi	Feed, speed, peck, tool	Direct Ra optimization
[5] Palanikumar, 2011	GFRP; L16 + grey	Speed, feed	Multi-response drilling quality
[7] Kivak et al., 2012	AISI 316; L16	Tool, speed, feed	Ra and thrust-force optimization
[8] Siddiquee et al., 2014	AISI 321; L18	Fluid, speed, feed, depth	Deep-drilling Ra optimization
[9] Motorcu et al., 2014	Waspaloy; L18	Tool, speed, feed, angle	Shows drill angle effect
[11] Parida et al., 2015	GFRP; L27 + RSM	Speed, feed, diameter	Ra modelling and validation

Methodology

1. Experimental Objective and Workpiece

The objective is to determine a robust set of drilling parameters that minimizes average surface roughness. For a practical implementation, rectangular AA6061-T6 specimens of approximately 100 mm x 60 mm x 10 mm may be used because aluminium alloy is

widely machined and allows stable roughness measurement. A CNC vertical machining centre and a 10 mm HSS twist drill are assumed. The methodology is transferable to steel or composite specimens provided that parameter limits, drill material, and cooling conditions are redefined before experimentation.

2. Selection of Control Factors and Levels

Three controllable factors are selected: spindle speed (A), feed rate (B), and drill point angle (C). The ranges are chosen to create clear low, medium, and high settings while remaining within normal drilling practice for the selected tool-workpiece pair. Cutting fluid, hole depth, tool diameter, clamping, and measurement procedure are held constant so that the effect of the selected control factors can be isolated.

Table 1. Control factors and levels used for the Taguchi L9 design.

Factor	Symbol	Level 1	Level 2	Level 3
Spindle speed (rpm)	A	600	1000	1400
Feed rate (mm/rev)	B	0.05	0.10	0.15

Point angle (degree)	C	100	118	135
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3. Experimental Procedure

Before each run, the workpiece is cleaned and rigidly clamped. A fresh or consistently reconditioned drill is installed and tool runout is checked. The programmed spindle speed and feed are set according to the L9 trial matrix. A through-hole is drilled to a constant depth under the same cooling condition. After drilling, chips are removed without scratching the bore. Surface roughness is measured along the hole wall with a calibrated stylus profilometer using the same cut-off length and evaluation length for all trials. Three Ra readings are taken at separated angular positions and averaged. The order of the nine trials should be randomized to reduce bias from tool heating, gradual wear, and machine drift.



Figure 1. Step-by-step methodology for Taguchi-based drilling parameter optimization.

4. Taguchi L9 Orthogonal Array and Statistical Analysis

With three factors at three levels, a standard L9 (3^3) orthogonal array requires only nine parameter combinations instead of the 27 combinations of a full factorial design. The factor assignment is shown in Table 2. Three roughness measurements are recorded for each run. Since minimum Ra is desired, the smaller-is-better S/N ratio is used: $S/N = -10 \log_{10}[(1/n) \sum(y_i^2)]$, where y_i is an individual roughness reading and n is the number of repeated measurements. A larger S/N ratio therefore represents a more desirable, less variable low-roughness condition.

Table 2. L9 experimental matrix.

Run	A: Speed (rpm)	B: Feed (mm/rev)	C: Point angle (degree)
1	600	0.05	100
2	600	0.1	118
3	600	0.15	135
4	1000	0.05	118
5	1000	0.1	135
6	1000	0.15	100
7	1400	0.05	135
8	1400	0.1	100
9	1400	0.15	118

The mean S/N ratio at each factor level is calculated and the delta between the maximum and minimum level means is used to rank factor influence. ANOVA is then applied to the repeated Ra observations to estimate the percentage contribution of each factor and to test statistical significance. The optimum setting is selected from the level with the highest S/N ratio for each factor. A confirmation experiment is finally conducted at the predicted optimum combination, even when that exact combination is not one of the L9 rows. The predicted mean at the optimum setting can be estimated from the grand mean and the selected factor-level means.

5. Quality-Control Measures

To improve repeatability, the same tool diameter, drilling depth, coolant strategy, clamping arrangement, and profilometer settings must be used throughout the experiment. Tool wear should be monitored, and either a new drill

should be used for each experimental block or the trial order should be randomized. Calibration of spindle speed and the roughness instrument should be documented. These controls are essential because Taguchi analysis ranks the factors included in the design; uncontrolled systematic variation can otherwise be misinterpreted as an effect of the selected drilling parameters.

Results

Important note: The numerical results in this section are an illustrative dataset constructed to demonstrate the analysis workflow. They should be replaced by measured laboratory data before the manuscript is represented as an experimental study.

Surface Roughness and S/N Ratio

Table 3. Illustrative roughness observations and smaller-is-better S/N ratios.

Run	Speed	Feed	Angle	Ra1	Ra2	Ra3	Mean Ra	S/N (dB)
1	600	0.05	100	1.302	1.342	1.352	1.332	-2.491
2	600	0.10	118	1.382	1.352	1.362	1.365	-2.705
3	600	0.15	135	1.812	1.862	1.842	1.839	-5.291
4	1000	0.05	118	0.890	0.920	0.900	0.903	0.882
5	1000	0.10	135	1.430	1.390	1.420	1.413	-3.006
6	1000	0.15	100	1.700	1.710	1.740	1.717	-4.694
7	1400	0.05	135	0.938	0.918	0.948	0.935	0.586
8	1400	0.10	100	1.258	1.278	1.238	1.258	-1.994
9	1400	0.15	118	1.388	1.418	1.408	1.405	-2.952

Table 4. S/N response table; larger S/N indicates better surface quality.

Factor	Level 1	Level 2	Level 3	Delta / Rank
Speed	-3.496	-2.272	-1.453	2.042 / 2
Feed	-0.341	-2.568	-4.312	3.971 / 1
Point angle	-3.060	-1.592	-2.570	1.468 / 3

Table 5. Illustrative ANOVA for repeated Ra observations.

Source	D F	SS	MS	F	Contribution (%)
Spindle speed	2	0.4413	0.2206	214.37	19.26
Feed rate	2	1.6026	0.8013	778.51	69.96
Point angle	2	0.2263	0.1132	109.95	9.88

Error	20	0.0206	0.0010	-	0.90
Total	26	2.2908	-	-	100.00

Discussion and Confirmation

The S/N response indicates that feed rate has the largest delta and is therefore the most influential factor in the illustrative dataset. The ANOVA gives the same ranking, with feed rate contributing about 69.96% of total variation, spindle speed 19.26%, and point angle 9.88%. This pattern is physically reasonable because increasing feed increases uncut chip thickness and thrust loading, which can increase feed marks and instability on the hole wall. The importance of feed is consistent with drilling studies in composites and steels that identified feed as a major contributor to roughness or related cutting responses [2,5,7,10].

Higher spindle speed improves the illustrative surface finish over the selected range, while the 118-degree point angle gives the best average

S/N response among the three geometries. Previous work also confirms that tool geometry can strongly affect drilled-surface roughness; Motorcu et al. [9] reported drill-bit angle as the largest contributor in Waspaloy, demonstrating that the dominant factor may change with material and tool system. The present result should therefore be interpreted as a methodological example rather than a universal ranking.

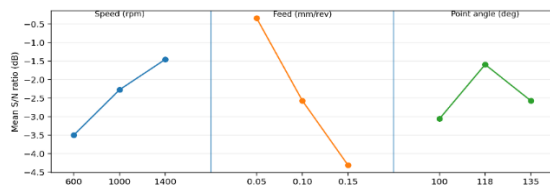


Figure 2. Main effects of parameter levels on the illustrative surface-roughness S/N ratio.

Predicted Optimum and Confirmation

The optimum level combination is A3-B1-C2: 1400 rpm spindle speed, 0.05 mm/rev feed, and 118-degree point angle. Using the grand mean and selected level means, the predicted mean roughness is approximately 0.78 micrometre. A confirmation experiment should be performed at this setting using at least three independent holes. For illustration, a confirmation means of 0.78 micrometre compared with the central-setting L9 condition of 1.413 micrometre corresponds to an improvement of about 44.8%. Agreement between predicted and confirmation values within the expected experimental scatter would validate the parameter choice.

Conclusion and Discussion

This paper presents a concise Taguchi methodology for optimizing drilling parameters to improve surface quality. A three-factor L9 orthogonal array reduces experimental effort while allowing spindle speed, feed rate, and point angle to be examined systematically. The method combines repeated Ra measurement, smaller-is-better S/N ratios, ANOVA, and a final confirmation test. In the illustrative analysis, feed rate is the dominant factor and the preferred parameter combination is 1400 rpm, 0.05 mm/rev, and 118-degree point angle. The principal advantage of the approach is not the specific numerical optimum but the reproducible decision process: define realistic factor ranges, control nuisance variables, randomize trials, quantify surface roughness consistently, rank factor effects with S/N analysis, verify them with ANOVA, and confirm the predicted optimum experimentally. For actual publication, the illustrative values must be replaced with

laboratory measurements and the method should report workpiece chemistry, tool condition, coolant, roughness standard, calibration, and confidence intervals. The approach can also be extended to multiple responses such as burr height, thrust force, circularity, and tool wear using grey relational analysis or desirability-based optimization, as demonstrated in earlier drilling research [1,5].

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