Statistical Optimization of Surface Roughness in CNC Turning of AISI 4041 low-alloy steel Using Taguchi Orthogonal Array

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Abstract: This paper investigates the optimization of surface roughness (Ra) in the CNC turning of AISI 4041 low-alloy steel using a Taguchi design and advanced Analysis of Variance (ANOVA). A Taguchi L25 orthogonal array was utilized to evaluate the individual and interactive effects of spindle speed, feed rate, and depth of cut. Experimental data were analyzed via signal-to-noise (S/N) ratios alongside a General Linear Model (GLM) ANOVA utilizing Type III sum of squares to isolate factor contributions. Quantitative analysis indicates that feed rate governs surface roughness variation, accounting for 95.24% of the total variance, whereas spindle speed exerts a minor influence (3.07%), and depth of cut is statistically negligible. The derived empirical model exhibits high predictive accuracy, evidenced by an R^2 value of 0.988. Optimal machining parameters were established at a minimized feed rate combined with a moderate spindle speed, successfully minimizing surface roughness. These outcomes establish empirical boundary conditions for the precision machining of AISI 4041 steel and offer a refined statistical framework for industrial process optimization.

Keywords: *Surface Roughness; Taguchi Method; ANOVA; CNC Turning; Feed Rate; Optimization; AISI 4041 low-alloy Steel.*

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I. INTRODUCTION

In modern manufacturing, productivity and product quality are fundamentally governed by interrelated machining responses, including material removal rate, tool wear, cutting forces, and surface roughness (Ra). During material transformation, a significant portion of mechanical energy is converted into thermal energy concentrated in proximity to the cutting edge. The magnitude of this heat generation fluctuates depending on the thermodynamic properties of the workpiece and the designated machining parameters, accelerating particularly at elevated cutting velocities [1]. Such temperature elevations directly accelerate flank wear and induce thermal alterations upon the machined surface layer, ultimately culminating in a compromised material removal rate and substandard surface finish. Practically, Ra is influenced by a multi-variable matrix: cutting conditions (speed, feed, and depth of cut), tool dynamics (material chemistry, nose radius, rake angle, cutting edge geometry, and vibration profiles), and workpiece physical attributes (alloy composition and hardness) [2], [3].

Consequently, establishing a precise selection of machining parameters is imperative to enhance cutting efficiency and ensure surface integrity.

Traditionally, machining parameter selection relies on production manuals or empirical expertise. However, this approach frequently yields suboptimal performance, driving up production expenses and restricting quality assurance. To mitigate these challenges, the deployment of statistical design of experiments alongside mathematical modeling has become pivotal for minimizing machining cost and time [4]–[6]. Experimental design methodologies offer a structured framework to organize trials systematically, allowing the resulting empirical data to be statistically modeled to derive definitive conclusions [7]. Among these, the Taguchi design method has emerged as a distinctively efficient approach for quality optimization. By implementing fractional designs known as orthogonal arrays, this methodology enables a comprehensive exploration of a multi-variable parameter space using a substantially reduced number of experimental runs [8].

The core philosophy of the Taguchi framework dictates that quality must be inherently integrated into product design rather than retroactively inspected, predominantly achieved by minimizing performance deviations from a specified target while tracking systemic economic losses [9]–[11]. Taguchi's parametric optimization entails a robust systematic flow incorporating orthogonal arrays, signal-to-noise (S/N) ratio

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analysis, and analysis of variance (ANOVA) to isolate uncontrollable noise variables and stabilize system performance.

The application of these statistical control strategies has been extensively documented across various alloy steel grades. For instance, investigations utilizing a Taguchi array and ANOVA evaluated the performance of conventional carbide inserts against wiper geometry tools during the turning of high-strength alloys [12]. Such literature underscores that tool geometry and feed configurations interact aggressively to drive surface topology. While prior literature focuses heavily on tool-steel optimization, further empirical data is required to establish exact boundary conditions for mid-carbon low-alloy structural steels under automated CNC environments.

The aim of the present investigation is to systematically model the individual effects of cutting parameters during the CNC turning of AISI 4041 low-alloy steel. By employing a Taguchi L25 orthogonal array design and advanced ANOVA, this study establishes the sensitivity and optimization thresholds of spindle speed, feed rate, and depth of cut toward minimizing workpiece surface roughness (Ra).

II. EXPERIMENTAL DETAILS

➢ *Workpiece Material*

The experimental investigations were executed utilizing AISI 4041 low-alloy steel, supplied as cylindrical round bars featuring a diameter of 50 mm and an axial length of 60 mm. This structural alloy finds extensive industrial utilization within automotive components and manufacturing assemblies owing to its balanced mechanical strength and toughness. The empirical chemical composition and core mechanical properties of the verified AISI 4041 steel substrate are systematized in Table 1 and Table 2, respectively.

Fig 1 AISI 4041 Work Piece

Table 1 Chemical Composition of AISI 4041

Element	**C**	**Fe**	**Si**	**Cr**	**Mn**	**Mo**	**S**	**P**
Wt %	0.38-0.43	96.8-97.69	0.15-0.3	0.8-1.10	0.75-1.0	0.15-0.25	0.04	0.035

Table 2 Mechanical Properties of AISI 4041Steel Substrate

parameter	**Ultimate Tensile Strength (Mpa)**	**Yield Strength (Mpa)**	**Brinell (BHN)**	**Rockwell (HRC)**	**Density (gm/cm^3)**
Value	655	415	197	50-55	7.85

➢ *Cutting Tool and Tooling Configuration*

For the continuous finishing operations, high-performance indexable uncoated carbide inserts possessing the standard ISO designation DNMG150612 were selected. The insert features a specialized PF chip-breaker geometry engineered for optimized chip control during fine-turning stages, alongside a thermally stable grade (4025) configured to withstand elevated interfacial temperatures during high-speed machining. The insert was rigidly secured onto a right-hand steel tool holder designated as PDJNL2525M16. To simulate typical industrial configurations, a water-soluble synthetic fluid (Viscool 5096) was supplied as a flooded coolant medium throughout all machining trials.

Fig 2 Carbide Insert with Tool Holder

➢ *Machining Lathe and Response Metrology*

The physical cutting experiments were completed under wet conditions using a rigid Hwacheon CNC lathe characterized by a maximum power output of 7.5 kW and a top spindle speed constraint of 3200 rpm. Prior to executing the structured experimental matrix, a skin-turning pass with a depth of cut of 0.5 mm was performed across all specimens to eliminate surface oxidation, rust scales, and geometric eccentricities, thereby guaranteeing structural homogeneity.

Following each machining run, the localized surface roughness (Ra) profile was measured using a portable Surtronic 3+ styli-profilometer developed by Taylor Hobson. Metrological parameters of the measurement hardware included a 400\ \mu\text{m} evaluation range, a 5\ \mu\text{m} diamond stylus tip radius, and a standardized diamond shape configuration. To capture representative and statistically unbiased data, Ra measurements were acquired at three different points around the machined perimeter of the specimens, and the arithmetic mean was recorded as the primary response variable (Ra).

➢ *Measurement of Surface Roughness*

The surface roughness of the machined components was

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measured at three different points by the use of Surtronic 3+ as shown in the Figure 3. Manufactured by Taylor Hobson, was employed. Surface roughness values were recorded at random locations around the perimeter of the specimens to obtain statistically meaningful data for any mixture element level. The surface roughness average (RA) was selected as the primary parameter in this investigation. (Measuring range: 400µm, Tip radius: 5µm, shape stylus: Diamond).

Fig 3 Experimental Setup for Measuring Surface Roughness

➤ *Design of Experiments (DoE)*

To analyze the multi-variable cutting domain efficiently, a systematic Design of Experiments (DoE) approach was adopted. The Taguchi method was implemented due to its robustness and capacity to lower experimental iterations without sacrificing statistical validity. Unlike full factorial setups, the Taguchi approach utilizes balanced orthogonal arrays to isolate independent factor effects with minimal experimental effort.

Three principal kinematic process parameters were mapped as independent control factors: spindle speed (V), feed rate (F), and depth of cut (D). Each variable was mapped across five distinct levels to cover the practical operating range encountered in industrial machining applications. The designated control variables and their operational levels are itemized in Table 3.

Table 3 Machining Parameters and Experimental Factor Levels

Factor	**Symbol**	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Spindle Speed (rpm)	V	50	190	390	450	880
Feed Rate (mm/rev)	F	0.05	0.15	0.25	0.35	0.45
Depth of Cut (mm)	D	0.25	0.50	1.00	1.50	2.00

Consequently, a Taguchi L25 (5^3) orthogonal array was selected to construct the experimental matrix. This layout maps the 25 unique trial configurations necessary to evaluate the variables while maintaining statistical balance. The structured experimental layout along with the experimentally captured Ra values is presented in Table 4.

Table 4 Taguchi L25 Orthogonal Array and Measured Ra Data

Exp.	**Spindle Speed (rpm)**	**Feed Rate (mm/rev)**	**Depth of Cut (mm)**	**Surface Roughness RA (µm)**
1	50	0.05	0.25	1.95
2	50	0.15	0.5	2.85
3	50	0.25	1.0	4.90
4	50	0.35	1.5	7.30
5	50	0.45	2.0	8.90
6	190	0.05	0.5	1.60
7	190	0.15	1.0	2.55
8	190	0.25	1.5	4.20
9	190	0.35	2.0	6.85
10	190	0.45	0.25	8.10
11	390	0.05	1.0	1.20
12	390	0.15	1.5	1.95
13	390	0.25	2.0	3.70
14	390	0.35	0.25	6.10
15	390	0.45	0.50	7.60
16	450	0.05	1.5	1.05
17	450	0.15	2.0	1.75
18	450	0.25	0.25	3.40
19	450	0.35	0.50	5.85
20	450	0.45	1.0	7.05
21	880	0.05	2.0	0.64
22	880	0.15	0.25	1.29

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23	880	0.25	0.50	3.53
24	880	0.35	1.0	7.41
25	880	0.45	1.5	8.78

III. RESULTS

Following the execution of the experimental trials based on the Taguchi L25 orthogonal array, the collected data were analyzed using mean response analysis, ANOVA and signal-to-noise (S/N) ratio to evaluate the influence of machining parameters on surface roughness and to establish a statistically robust interpretation of the results.

➢ *Effect of Machining Parameters on Surface Roughness Using Mean Response Analysis*

To track how individual kinematic inputs modify surface generation, mean response analysis was completed across all parameter levels. These aggregated values are compiled in Table 5.

Table 5 Mean Ra Values across Factor Levels

Factor	Symbol	Level 1	Level 2	Level 3	Level 4	Level 5
Spindle Speed (rpm)	V	5.18	4.66	4.11	3.82	4.33
Feed Rate (mm/rev)	F	1.29	2.08	3.95	6.70	8.09
Depth of Cut (mm)	D	4.17	4.29	4.62	4.66	4.37

As observed in Table 5, shifting the spindle speed upward from 50 to 450 rpm yields a progressive reduction in mean Ra. This behavior complies with cutting mechanics: higher speeds increase localized cutting zone temperatures, reducing built-up edge (BUE) formation and supporting stable chip flow. However, increasing the speed further to 880 rpm causes a slight deterioration in Ra (4.33 µm). This shift marks the onset of dynamic instability, where high-velocity turning induces forced vibrations and thermal softening of the tool edge, degrading surface topology.

Feed rate exhibits a dominant, highly sensitive impact on Ra. Shifting feed inputs from 0.05 to 0.45 mm/rev triggers a sharp, non-linear surge in Ra from 1.29 to 8.09µm. Kinematically, ideal surface roughness is proportional to the square of the feed rate ($Ra \approx F^2 / (32.r_\varepsilon)$) due to the geometric footprint of feed marks. Physically, increased feed inputs broaden the chip thickness and cutting forces, which intensify plastic deformation and material side flow along the tool shoulder.

Conversely, changing the depth of cut reveals a negligible influence on Ra. This lines up with classical machining theory where depth of cut maps directly to material removal rate and bulk force metrics rather than modifying the localized shearing mechanisms that generate surface features. Its limited impact indicates that surface formation is dominated by tool-workpiece interaction geometry rather than bulk material removal.

➢ *ANOVA and Statistical Significance*

To isolate and quantify the variance contributions of each factor, a General Linear Model (GLM) ANOVA utilizing a Type III sum of squares was performed. The statistical analysis outputs are compiled in Table 6.

Table 6 GLM ANOVA Results for Surface Roughness (RA)

Source Factor	Type III Sum of Squares	Df	Mean Square	F	Sig.	Contribution(%)
V	5.497	4	1.374	7.806	.002	3.07%
F	170.831	4	42.708	242.593	.000	95.24%
D	.903	4	.226	1.283	.330	0.50%
Error	2.113	12	.176			1.18%
Corrected Total	179.344	24				100%
a. R Squared = .988 (Adjusted R Squared = .976)						

The ANOVA calculations reveal that the feed rate is the primary driver of variance, holding a 95.24% contribution margin with an extremely high F-value of 242.593 and absolute statistical significance ($p < 0.001$). This overwhelming contribution confirms that surface roughness is predominantly governed by feed-induced surface generation mechanisms. Spindle speed, while statistically significant ($p = 0.002$), controls only a 3.07% contribution slice, indicating its role is secondary and mainly associated with improving cutting stability. Depth of cut is confirmed to be statistically insignificant ($p = 0.330$), accounting for just 0.50% of total variance. The low error contribution (1.18%) reflects high experimental accuracy. Moreover, the model fit metrics ($R^2 = 0.988$, Adjusted R2 = 0.976) confirm excellent predictive capability.

➢ *Mechanistic Interpretation of Results (Advanced Insight)*

The dominance of feed rate can be explained through the fundamental mechanics of surface generation in turning. The theoretical surface roughness (RA) is primarily governed by the kinematic relationship between tool geometry and feed motion, where the feed rate directly determines the spacing and height of surface irregularities.

Furthermore, higher feed rates increase the contact stress and plastic deformation at the tool–work piece

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interface, leading to material side flow and irregular surface formation. This explains the exponential increase in roughness observed experimentally.

The influence of spindle speed is mainly related to thermal and tribological effects. At moderate speeds, improved chip evacuation and reduced built-up edge formation enhance surface quality. However, at excessively high speeds, thermal softening and tool vibration may offset these benefits.

The negligible effect of depth of cut suggests that, within the selected range, its influence is limited to subsurface deformation rather than surface topology, which aligns with classical machining theory.

➢ *Signal-to-Noise (S/N) Ratio and Robust Optimization*

The Taguchi method employs the signal-to-noise (S/N) ratio as a robust statistical measure to evaluate the performance of machining parameters under varying conditions. In this study, the objective is to minimize surface roughness (RA); therefore, the "smaller-the-better" criterion was adopted. This formulation ensures that both the mean and variability of the response are simultaneously considered, thereby enhancing the reliability of the optimization process.

The S/N ratio for the smaller-the-better characteristic is defined as:

$$S/N = -10log_{10}\left(\sum SR^2/n\right)$$

The S/N ratio values were calculated for each experimental run, and the average S/N ratios at each level of the machining parameters were determined. The response graphs based on S/N ratios provide a clear indication of the optimal levels of each factor. A higher S/N ratio corresponds to better performance, i.e., lower surface roughness with reduced variability.

As showing in Table (7) and Figure 4 with the help of Minitab16 software, that The analysis of S/N ratio trends reveals that the feed rate (F) exhibits the most significant influence on surface roughness, as indicated by the steep variation in S/N values across its levels. In contrast, spindle speed (V) shows a moderate effect, while depth of cut (D) demonstrates a relatively minor influence. These findings are consistent with the results obtained from the mean response analysis and ANOVA, confirming the robustness and consistency of the experimental outcomes.

Table 7 Signal-to-Noise (S/N) Characteristics Given by Taguchi

Exp.	Spindle Speed (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)	Surface Roughness RA (µm)	S/N
1	50	0.05	0.25	1.95	-5.80
2	50	0.15	0.5	2.85	-9.09
3	50	0.25	1.0	4.90	-13.80
4	50	0.35	1.5	7.30	-17.27
5	50	0.45	2.0	8.90	-18.99
6	190	0.05	0.5	1.60	-4.08
7	190	0.15	1.0	2.55	-8.13
8	190	0.25	1.5	4.20	-12.47
9	190	0.35	2.0	6.85	-16.71
10	190	0.45	0.25	8.10	-18.17
11	390	0.05	1.0	1.20	-1.58
12	390	0.15	1.5	1.95	-5.80
13	390	0.25	2.0	3.70	-11.36
14	390	0.35	0.25	6.10	-15.71
15	390	0.45	0.50	7.60	-17.62
16	450	0.05	1.5	1.05	-0.42
17	450	0.15	2.0	1.75	-4.86
18	450	0.25	0.25	3.40	-10.63
19	450	0.35	0.50	5.85	-15.34
20	450	0.45	1.0	7.05	-16.96
21	880	0.05	2.0	0.64	3.88
22	880	0.15	0.25	1.29	-2.21
23	880	0.25	0.50	3.53	-10.96
24	880	0.35	1.0	7.41	-17.39
25	880	0.45	1.5	8.78	-18.87

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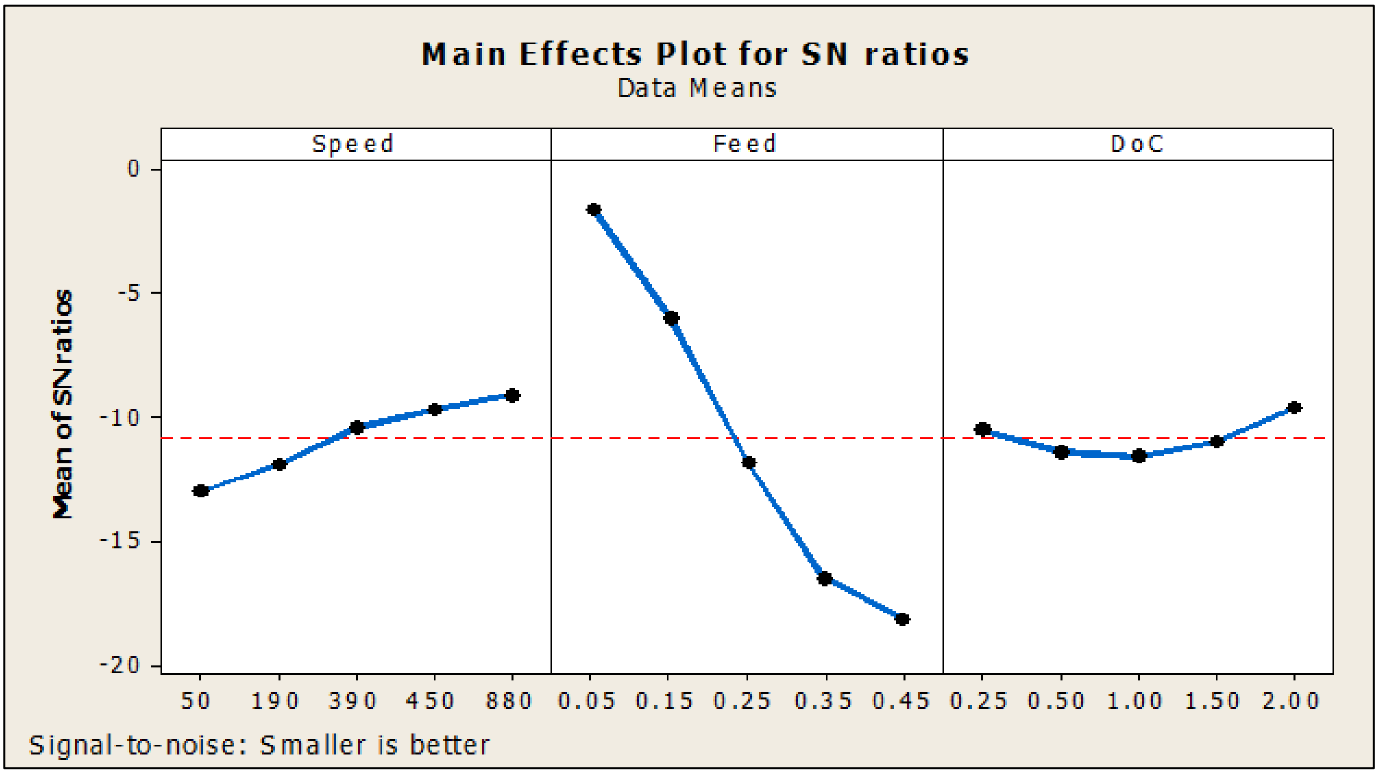

Fig 4 Main Effects Plot for SN Ratios of RA

A higher S/N ratio corresponds to optimal performance with reduced variability. The analysis of S/N ratio trends reveals that feed rate exhibits the steepest variation, confirming its dominant control over surface quality. Based on the robust evaluation of S/N responses, the optimal parameter combination for minimizing surface roughness (Ra) was established as:

- Spindle speed: 450 rpm
- Feed rate: 0.05 mm/rev
- Depth of cut: **1.5** mm

This combination ensures minimal surface irregularities while maintaining process stability and efficiency.

IV. CONCLUSION

This study presented a comprehensive statistical investigation of surface roughness in CNC turning of AISI 4041 low-alloy steel using the Taguchi method combined with ANOVA and regression modeling. The Taguchi L25 orthogonal array proved to be an efficient experimental design for evaluating the effects of machining parameters while reducing the number of required experiments without compromising statistical reliability.

The results clearly demonstrated that feed rate is the most influential factor affecting surface roughness, accounting for approximately 95.24% of the total variation. This finding confirms that surface generation during turning is primarily governed by feed-induced geometrical effects. Spindle speed exhibited a statistically significant but relatively small contribution (3.07%), whereas depth of cut was found to be statistically insignificant within the investigated operating range.

The developed regression model showed excellent predictive performance with a coefficient of determination of $R^2 = 0.988$, indicating a strong agreement between predicted and experimental values. Residual analysis further confirmed the adequacy and reliability of the proposed model.

Based on the combined evaluation of mean response analysis, signal-to-noise ratio, and ANOVA, the optimum machining conditions for minimizing surface roughness were identified as a feed rate of 0.05 mm/rev, spindle speed of 450 rpm, and low depth of cut. These conditions provide superior surface quality while maintaining machining stability.

The obtained results are in strong agreement with previous studies reported in the literature. Several researchers, including Davim J. P. and Gaitonde V. N., concluded that feed rate is the dominant parameter affecting surface roughness in turning operations, which is consistent with the findings of the present study. Likewise, the observed secondary influence of spindle speed agrees with the work of Suresh P. V. S., who reported that higher cutting speeds improve surface finish through better chip formation and reduced built-up edge effects. The negligible influence of depth of cut is also supported by the findings of Thamizhmanii S., who reported a limited effect of this factor on surface roughness under moderate cutting conditions.

A notable outcome of the present investigation is the exceptionally high contribution of feed rate (95.24%) compared with values commonly reported in the literature, which often range between 50% and 70%. This difference may be attributed to the application of Type III ANOVA, which isolates the pure effect of each machining parameter and provides a more accurate assessment of factor contributions. Consequently, the present study not only confirms established machining theory but also provides deeper insight into the quantitative dominance of feed rate through advanced statistical analysis.

Overall, the close agreement between the present findings and previous research validates the reliability of the experimental design, the robustness of the statistical models, and the effectiveness of the proposed optimization approach for precision machining applications. Future studies may incorporate tool wear, vibration monitoring, and thermal effects to further improve model accuracy and industrial applicability.

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