

EXPERIMENTAL AND STATISTICAL ASSESSMENT OF POCKET MILLING PARAMETERS FOR SS304 USING TAGUCHI EXPERIMENTAL DESIGN

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Abstract

Purpose: Pocket milling of AISI 304 stainless steel requires appropriate selection of cutting conditions to obtain acceptable surface quality without unnecessarily reducing material removal. This study examines the effects of spindle speed, feed rate, and depth of cut on surface roughness and identifies the best observed parameter combination within the tested range.

Design/methodology/approach: Nine pocket-milling trials were conducted on a VMC 850 using a 12 mm TiAlN-coated carbide end mill. A Taguchi L9 orthogonal array was employed with spindle speeds of 1000, 1250, and 1500 rpm, feed rates of 300, 600, and 900 mm/min, and depths of cut of 0.2, 0.4, and 0.6 mm. Surface roughness was measured using a Mitutoyo SJ-301 in terms of arithmetic average roughness, root mean square roughness, and maximum height. Material removal rate was calculated from the machining conditions. Minitab was used for signal-to-noise analysis, main-effects analysis, analysis of variance, first-order regression, and response-surface visualization.

Findings: Feed rate showed the clearest practical effect on surface roughness, although none of the three factors was statistically significant at the 5% level. The lowest measured roughness occurred at 1250 rpm, 300 mm/min, and 0.4 mm depth of cut, giving 1.992 μm arithmetic average roughness, 2.456 μm root mean square roughness, and 11.101 μm maximum height. The highest calculated material removal rate was 6480 mm³/min at 900 mm/min feed and 0.6 mm depth of cut. The first-order regression model gave an R^2 of 14.3%, indicating limited predictive capability. No independent confirmation experiment was conducted.

Practical implications: The identified setting provides a practical starting point for achieving lower surface roughness under the investigated machine, tool, material, and pocket geometry. The results also show the trade-off between surface quality and material removal rate and provide a basis for replicated and broader multi-response machining studies.

1. Introduction

Stainless steel 304 (SS304) is commonly selected for parts that need corrosion resistance together

with adequate mechanical strength and service life. During machining, its relatively low thermal conductivity, tendency to work harden and

tendency to adhere to the cutting tool can increase the thermal and mechanical demands on the process. These characteristics may encourage material buildup at the cutting edge and accelerate tool degradation, thereby affecting surface finish and productivity. Earlier work has likewise identified American Iron and Steel Institute (AISI) 304 as a demanding material for end-milling and interrupted-cutting applications [1,2].

Experimental evidence indicates that American Iron and Steel Institute (AISI) 304 does not respond uniformly to changes in cutting conditions or tool characteristics. In a Taguchi L16 investigation, Zhou associated lower feed and intermediate cutting-speed levels with improved surface characteristics and changes in work-hardening response [3]. Wu et al. connected tool-chip friction, thermal effects and work hardening with wear behavior [4]. Shah et al. reported that the substrate properties of carbide tools can affect flank wear and edge chipping during intermittent milling [5].

When several machining factors must be compared but the number of experiments must remain small, a Taguchi arrangement provides an efficient experimental structure. The orthogonal layout permits the selected factor levels to be examined systematically, while signal-to-noise (S/N) measures can be interpreted together with analysis of variance (ANOVA) and regression results. Similar machining investigations have combined compact Taguchi designs with Minitab and these statistical tools [6-9].

This study is centered on SS304 pocket milling on a vertical machining center (VMC 850). Spindle speed, feed rate and axial depth of cut were assigned three levels in an L9 matrix, and each trial was characterized using arithmetic average roughness (Ra), root mean square roughness (Rq), maximum height roughness (Rz) and a geometry-derived material removal rate (MRR). Related publications address surface integrity, tool monitoring and tool-material behavior under different experimental conditions [18-20]. The present contribution is consequently a defined machine-tool-material dataset with multiple roughness measures, a productivity calculation and supporting statistical interpretation. The selected setting is

described only as the best measured condition within these nine trials, not as a general optimum for SS304 milling.

1.1. Research Objectives

- To examine how spindle speed, feed rate and axial depth of cut affected the measured surface quality of the SS304 pocket.
- To compare the practical contribution of the three machining variables using Taguchi signal-to-noise results and ANOVA.
- To examine the observed relationship between surface finish and the calculated material removal rate.
- To identify the tested combination that produced the lowest measured surface roughness.
- To use Minitab-based S/N, ANOVA, first-order trend fitting and exploratory desirability analysis within the design of experiments (DOE) framework.

1.2. Literature Review and Research Gap

Recent work on AISI 304 increasingly considers surface integrity together with tool performance rather than relying on a single roughness metric. Zhou used a Taguchi L16 arrangement to examine the influence of feed and cutting speed on roughness, microhardness and corrosion-related surface characteristics [3]. Wu et al. investigated a modified cutting tool and discussed friction, wear and chip behavior [4]. Shah et al. examined carbide-substrate structure in relation to hardness, fracture toughness, flank wear and edge chipping [5]. Together, these studies demonstrate the need to consider both the finished surface and the condition of the cutting tool.

Condition monitoring and data-oriented methods are also being combined with small experimental designs. A 2025 study on AISI 304, for example, coupled Taguchi experimentation with acoustic monitoring and used an I-Kaz feature to examine flank-wear behavior [2]. This type of approach illustrates how a compact DOE can serve as the experimental foundation for later integration with direct condition-monitoring measurements. The specific gap considered in this work concerns pocket milling of SS304 on a VMC 850 using a three-factor, three-level L9 plan. Ra,

Rq and Rz were measured for every trial, while MRR was calculated from the stated cutting geometry. Factor effects were then examined through S/N analysis, ANOVA, first-order fitting and surface plots. The resulting evidence should be read as a controlled case study for the stated machine, tool and pocket configuration rather than as a general optimization applicable to all SS304 milling conditions.

Recent machining literature commonly evaluates surface quality together with productivity or tool-condition information. Studies on AISI 304 have applied Taguchi designs to surface integrity, while other work has added tool monitoring and detailed surface characterization [2,7,8,10]. Related stainless-steel investigations have also combined Taguchi and response-surface methods for multi-response machining assessment [11]. The present analysis uses the

available project measurements from an L9 experiment and treats Ra, Rq and Rz as measured responses, with MRR calculated separately from the specified geometry.

2. Materials and Methods/Methodology

The principal equipment and experimental conditions are summarized in Table 1.

2.1. Workpiece, Machine and Tool

The machining trials were carried out on a VMC 850 using SS304 workpieces and a 12 mm titanium aluminum nitride (TiAlN)-coated carbide end mill. The pocket dimensions and specimen-preparation procedure were retained from the original final-year project record. Figures 1 and 2 show the actual machining arrangement and the machined specimens used for the nine trials.

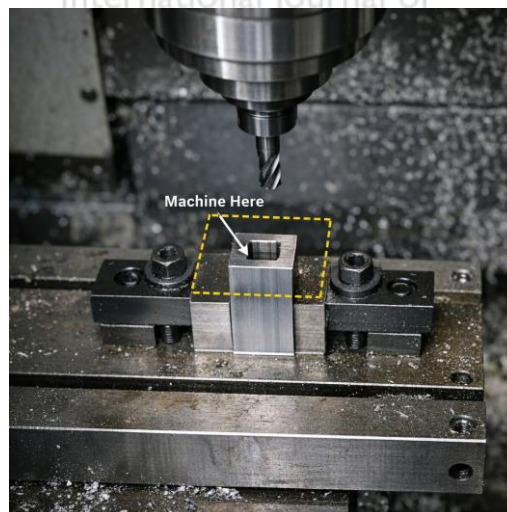


Figure 1. Machining arrangement used for the SS304 pocket-milling experiments on the VMC 850.



Figure 2. SS304 pocket specimens produced during the experimental trials.

Table 1. Principal experimental equipment and conditions.

Item	Specification
Workpiece	SS304 stainless steel
Machine	VMC 850 vertical machining center
Cutting tool	12 mm titanium aluminum nitride (TiAlN)-coated carbide end mill
Surface roughness instrument	Mitutoyo SJ-301
Machining feature	Pocket
DOE	Taguchi L9 orthogonal array
Statistical software	Minitab

The three control factors and their tested levels are given in Table 2.

2.2. Machining Parameters and Levels

Table 2. Control factors and experimental levels.

Factor	Symbol	Unit	Level 1	Level 2	Level 3
Spindle speed	N	rpm	1000	1250	1500
Feed rate	Vf	mm/min	300	600	900
Depth of cut	ap	mm	0.2	0.4	0.6

2.3. Taguchi Experimental Design

The nine experimental settings were selected from the Taguchi L9 array, which covers three factors at three levels without requiring all 27 possible combinations. For Ra, the smaller-is-better S/N expression was used. Each setting had only one observation, giving $n = 1$. Thus, the S/N values are mathematical transformations of the individual Ra measurements and cannot establish repeatability

or resistance to measurement noise. The design approach is consistent with established Taguchi methodology [12,13].

$$\eta = -10 \log_{10}[(1/n) \sum y_i^2] \quad (1)$$

Here, η is the signal-to-noise statistic, n is the number of observations and y_i denotes the measured roughness.

The resulting nine-run experimental matrix is presented in Table 3.

Table 3. Taguchi L9 experimental matrix.

Run	N (rpm)	Vf (mm/min)	ap (mm)
1	1000	300	0.2
2	1000	600	0.4
3	1000	900	0.6
4	1250	300	0.4
5	1250	600	0.6
6	1250	900	0.2
7	1500	300	0.6
8	1500	600	0.2
9	1500	900	0.4

The measured roughness values and calculated MRR for all nine runs are listed in Table 4.

2.4. Response Measurements and MRR Calculation

Ra, Rq and Rz came directly from the surface-roughness measurements. MRR, in contrast, was estimated from the cutting geometry because no

machine-controller removal-rate record was available. The relation used is given in (2). These calculated values are used only to compare relative productivity among the trials and should not be read as directly measured instantaneous machine output.

$$MRR = w \cdot a_p \cdot Vf = 12 \times a_p \times Vf \quad (2)$$

Here, $w = 12$ mm based on the diameter of the end mill.

Table 4. Experimental roughness responses and calculated MRR.

Run	Ra (μm)	Rq (μm)	Rz (μm)	MRR (mm^3/min)
1	2.714	3.896	28.479	720
2	3.407	4.263	24.646	2880
3	4.561	6.139	30.433	6480
4	1.992	2.456	11.101	1440
5	4.262	7.604	70.675	4320
6	3.105	3.761	16.214	2160
7	3.577	7.712	27.895	2160
8	7.053	9.333	54.185	1440
9	3.006	3.723	16.602	4320

2.5. Statistical Analysis

Minitab was used for the S/N calculations, main-effect plots, ANOVA, residual checks, interaction display, first-order regression and desirability analysis. Since each of the nine conditions was observed only once, the numerical results were considered together with the factor trends and machining context. The first-order Ra model gives $R^2 = 14.3\%$, so it serves as a description of the observed pattern rather than a validated predictor. The available nine-run design also does not contain enough observations for a complete three-factor quadratic response-surface model.

The statistical scope of the experiment is therefore limited to compact comparison of the tested main effects. A three-factor quadratic model would require 10 coefficients: one intercept, three linear terms, three two-factor interactions and three squared terms. With only nine observations, such a model cannot be estimated with residual degrees of freedom. The

plotted surfaces are consequently first-order visualizations over the tested region, not validated quadratic response-surface methodology (RSM) results. Designs such as central composite and Box-Behnken arrangements use additional runs to estimate curvature [14–16].

3. Results

3.1. Surface Roughness Response

The nine trials produced noticeably different surface-roughness responses. Run 4 had the smallest values of all three reported measures: Ra = 1.992 μm , Rq = 2.456 μm and Rz = 11.101 μm . Run 8 produced the largest Ra and Rq values, 7.053 and 9.333 μm , whereas the largest Rz, 70.675 μm , occurred in Run 5. The differing locations of the maximum values show why the surface cannot be characterized completely by Ra alone. The three roughness measures are compared in Figure 3.

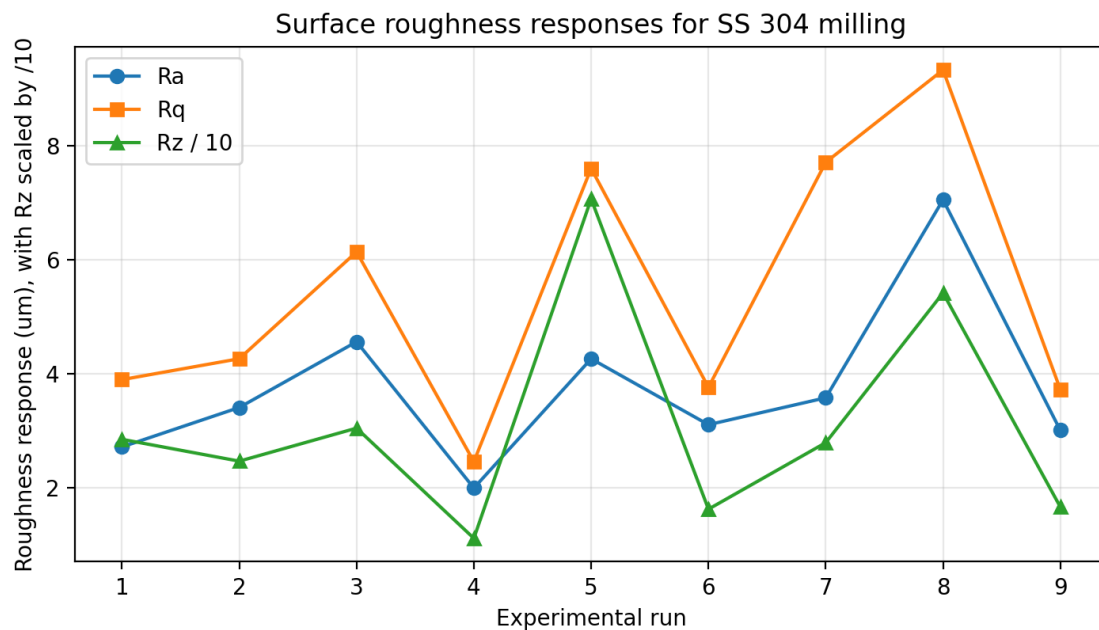


Figure 3. Surface-roughness measurements for Ra, Rq and Rz over the nine experimental conditions.

3.2. Effect of Machining Parameters

Of the three control variables, feed rate showed the strongest practical relationship with Ra over the tested range. A higher feed increases chip load and can leave more pronounced feed marks, which agrees with the measured trend. The effect of spindle speed was non-monotonic, with 1250 rpm giving lower roughness than the two other speed levels. For depth of cut, the lowest observed roughness likewise occurred at the intermediate value of 0.4 mm.

3.3. Productivity–Surface-Quality Trade-Off

The calculated MRR values show a clear contrast between removal productivity and surface finish. Run 3 gave the largest calculated rate, 6480 mm³/min, using 900 mm/min feed and 0.6 mm depth of cut, but its Ra was 4.561 μm. Run 4 produced the smallest measured Ra, while its calculated MRR was only 1440 mm³/min. Thus, the trial with the greatest calculated removal rate was different from the trial that produced the smoothest measured surface. The run-by-run comparison is shown in Figure 4.

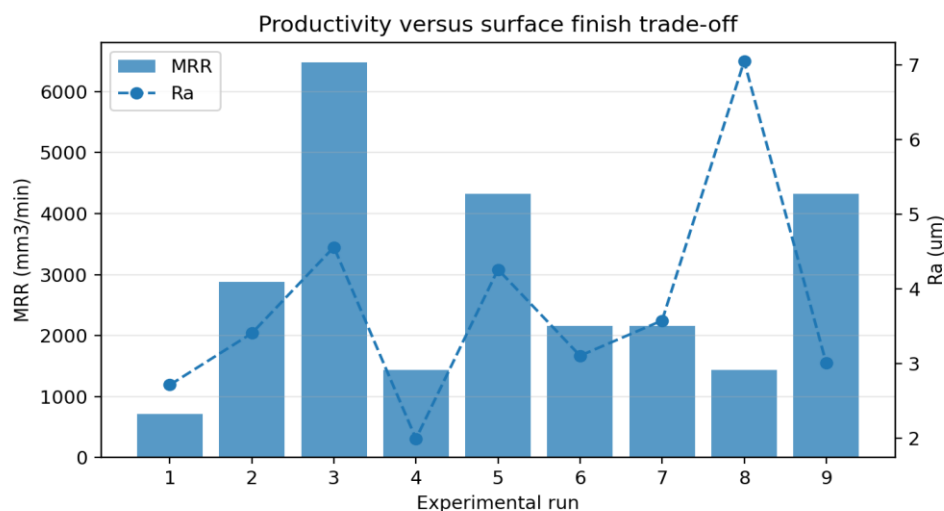


Figure 4. Comparison of calculated MRR with measured Ra for the nine trials.

3.4. Taguchi-Selected Condition and ANOVA Interpretation

The smaller-is-better S/N results point to the Run 4 levels—1250 rpm, 300 mm/min and 0.4 mm—as the preferred combination within the L9 matrix. This run also gave the lowest Ra, Rq and Rz values. From a practical-effect perspective, feed rate showed the strongest influence,

followed by depth of cut and spindle speed. Since no independent confirmation trial was carried out, these levels are reported as the best observed condition in the present experiment rather than as a universally verified optimum. The main-effect, residual, and interaction plots are shown in Figures 5–8.

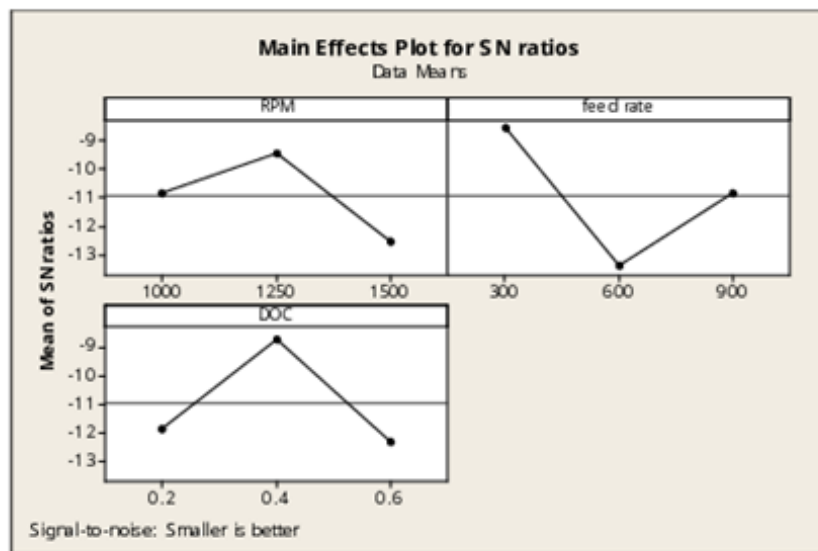


Figure 5. Main effects of the machining factors on the smaller-is-better S/N response for Ra.

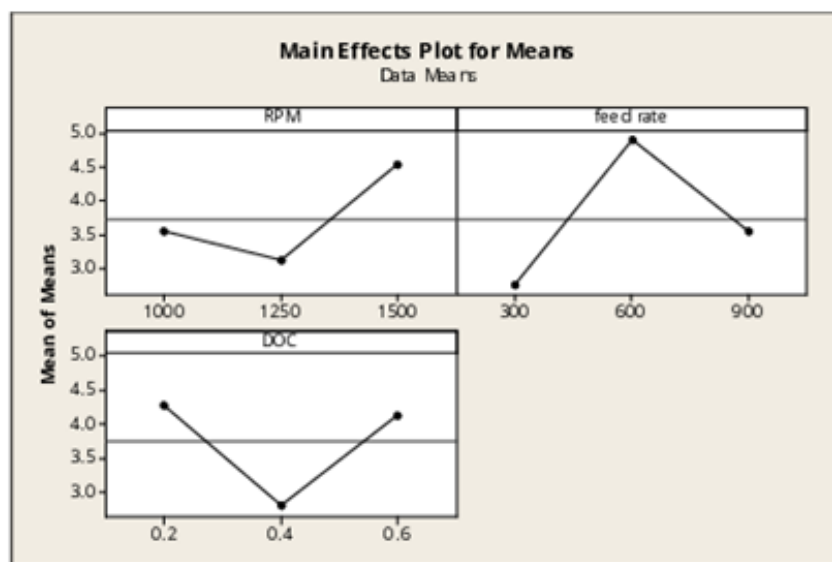


Figure 6. Main effects of the machining factors on the measured Ra response.

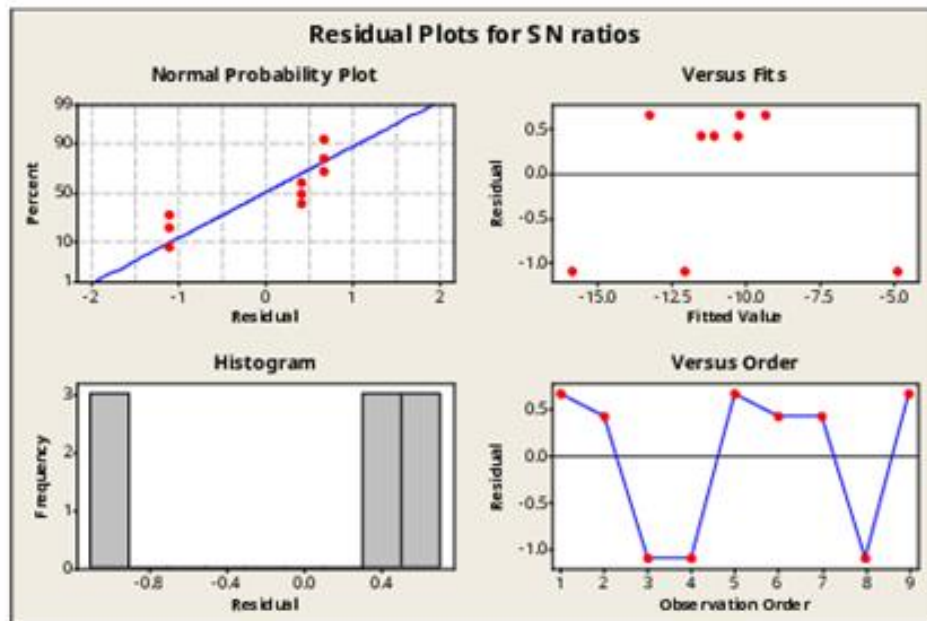


Figure 7. Residual diagnostic plots obtained from the Taguchi S/N analysis.

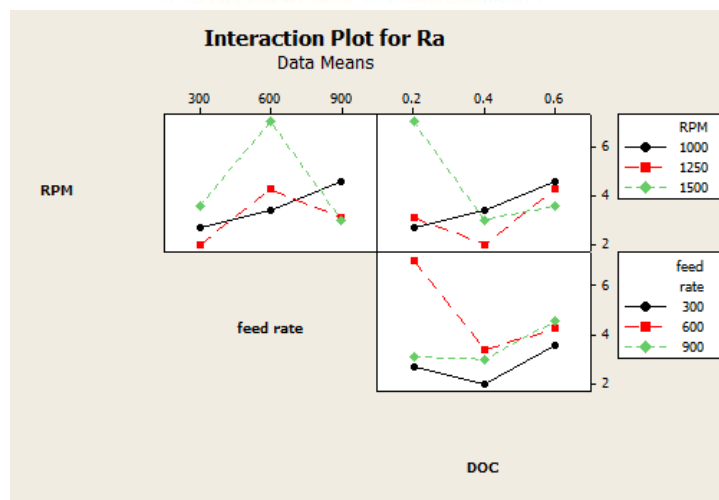


Figure 8. Ra interaction display; interpretation is descriptive because the L9 experiment has no replication for an independent interaction significance test.

The ANOVA findings must be considered in view of the small residual degrees of freedom. Only two residual degrees of freedom remain in the nine-run design, and, because the trials were not repeated, this residual term represents pooled unexplained variation rather than a direct measure of repeatability. The p-values were 0.281 for spindle speed, 0.136 for feed rate and 0.198 for depth of cut. Feed rate produced

the largest F statistic, 6.34, and the strongest practical effect, although its p-value is above 0.05. Accordingly, the ANOVA is used to compare the behavior observed in this dataset, not to establish a general statistical effect for SS304 milling. The ANOVA results are summarized in Table 5. The corresponding contour maps are shown in Figure 9.

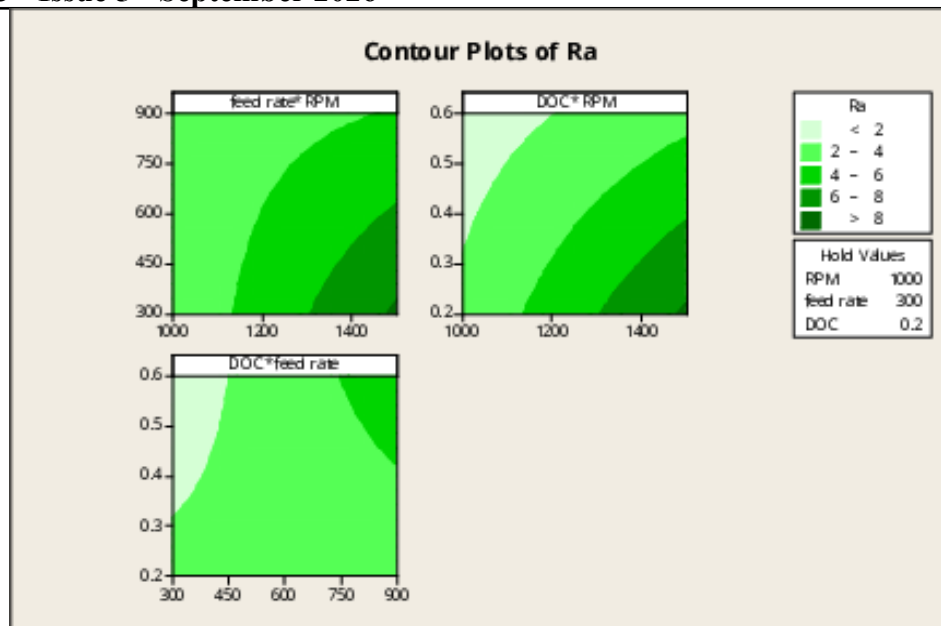


Figure 9. Ra contour maps over the tested combinations of machining parameters.

Table 5. ANOVA results for the reported Ra model.

Source	Degrees of freedom	Adjusted square	mean	F-value	p-value
Spindle speed (N)	2	7.049		2.55	0.281
Feed rate (Vf)	2	17.486		6.34	0.136
Depth of cut (ap)	2	11.198		4.06	0.198
Residual error	2	2.760		—	—
Total	8	—		—	—

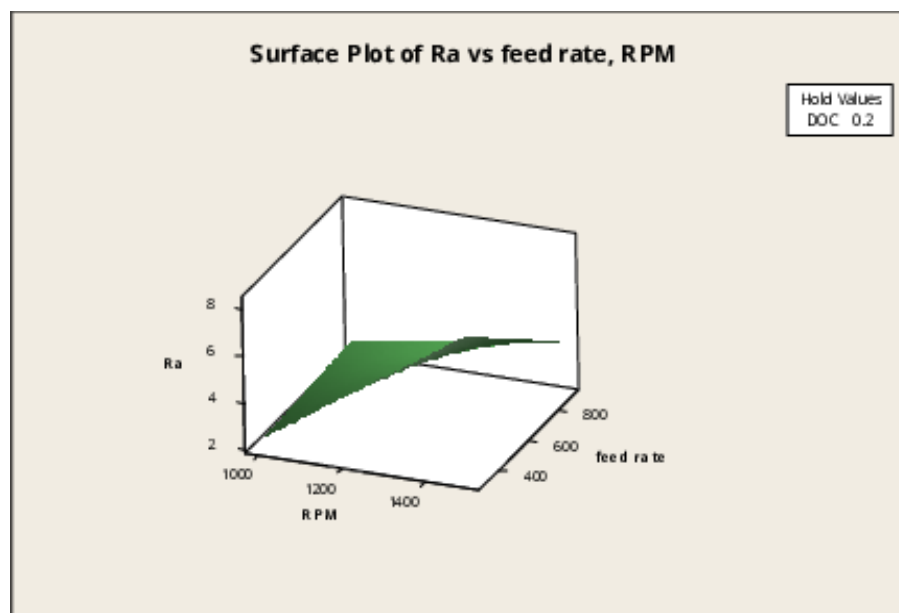


Figure 10. First-order fitted-surface view of Ra within the experimental parameter region.

The consolidated parameter-selection findings are summarized in Table 6.

Table 6. Consolidated parameter-selection findings.

Analysis item	Finding
Dominant practical factor	Feed rate
Preferred spindle speed level	1250 rpm
Preferred feed-rate level	300 mm/min
Preferred depth-of-cut level	0.4 mm
Lowest measured Ra	1.992 μm (Run 4)
Highest measured Ra	7.053 μm (Run 8)
Highest calculated MRR	6480 mm^3/min (Run 3)

3.5. First-Order Regression and Surface Visualization

The first-order relationship fitted to Ra is given in (3). With $R^2 = 14.3\%$, the linear expression explains only a limited portion of the observed variation and is therefore used for trend description rather than accurate prediction. The associated surface plots illustrate this fitted first-order behavior across the tested ranges. They are not quadratic RSM models: a three-factor quadratic equation contains 10 coefficients, whereas only nine observations are available here. Additional response-surface runs would be required to estimate curvature reliably [14–16]. Figure 10 shows the fitted first-order surface.

$$Ra = 0.64 + 0.00197N + 0.00133Vf - 0.39a_p \quad (3)$$

Run 4 was also selected by the exploratory desirability calculation, in agreement with its lowest measured Ra, Rq and Rz. Its calculated MRR was lower than that obtained under the higher feed and depth combinations. Because the project records do not preserve the complete desirability settings and importance weights, this outcome is retained as an exploratory project-level selection rather than a separately reproducible optimization result. The additional surface and desirability views are shown in Figures 11 and 12.

RSM response surface for Ra at DOC = 0.4 mm

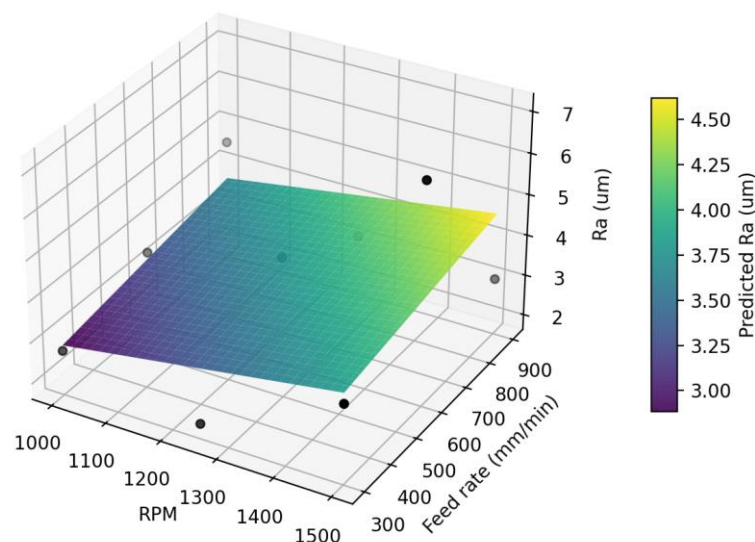


Figure 11. First-order Ra surface view at a depth of cut of 0.4 mm.

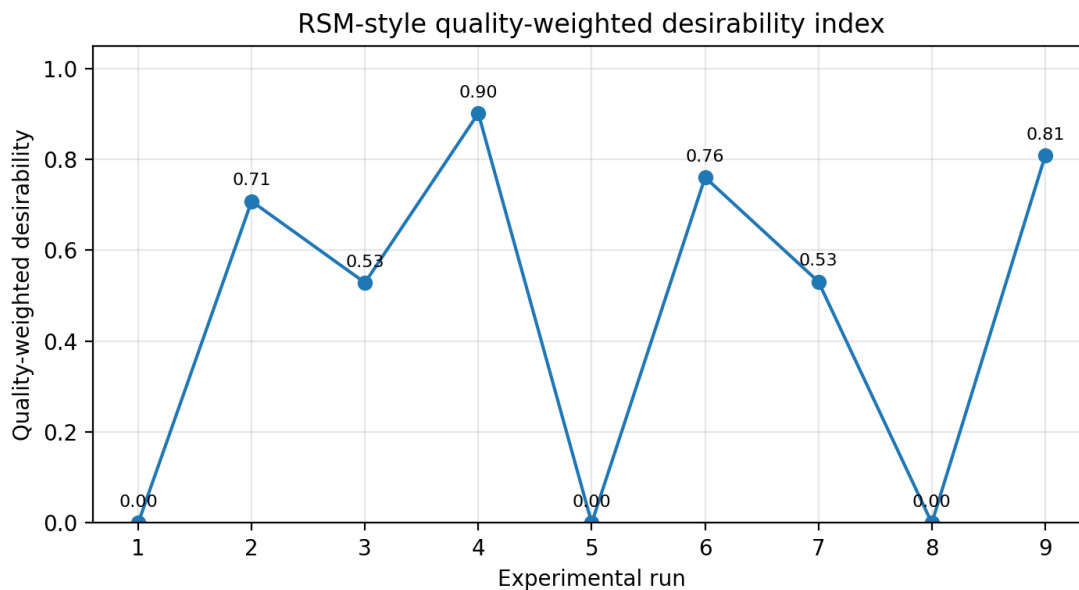


Figure 12. Exploratory quality-weighted desirability values for the nine DOE conditions.

4. Discussion

Recent studies published during 2024–2026 provide additional context on machining-condition selection, surface integrity and tool behavior in stainless-steel processing. These studies are used here to frame the present

findings; they are not treated as direct validation because their machines, tools, materials, geometries or experimental designs differ from the present setup.

The present case study is positioned against selected recent literature in Table 7.

Table 7. Positioning of the present study relative to selected recent literature.

Study	Material / focus	Method	Key relevance to present work
Kumar et al. (2023) [9]	SS304 end milling	Taguchi + Grey relational analysis (GRA)	Supports multi-response parameter optimization.
Jadhav & Sahai (2024) [6]	AISI 4140	Taguchi L9 + Minitab + ANOVA + regression	Confirms the continued usefulness of compact DOE for machining optimization.
Zhou (2025) [3]	AISI 304 milling	Taguchi L16	Links feed/speed with roughness and broader surface integrity.
Wu et al. (2025) [4]	AISI 304 tool wear	Tool modification + simulation + tests	Highlights friction, thermal effects and tool-wear control.
I-Kaz study (2025) [2]	AISI 304 dry milling	Taguchi L18 + acoustic monitoring	Demonstrates integration of DOE with direct tool-wear monitoring.
Shah et al. (2026) [5]	AISI 304 end milling	Carbide substrate study	Shows the influence of tool microstructure on flank wear and edge chipping.

The present findings are generally in line with the broader observation that machining conditions influence both surface quality and productivity. The study itself, however, is deliberately bounded by one VMC 850, one SS304 pocket geometry, one 12 mm TiAlN-coated carbide end mill and the tested parameter levels. Its main contribution is the compact L9 dataset and the joint examination of three roughness measures with a calculated productivity indicator. Applying the selected condition to other machines, tools or geometries would require independent confirmation.

5. Conclusion

A nine-run Taguchi L9 experiment was used to examine spindle speed, feed rate and depth of cut, with each variable represented at three levels.

Across the tested range, feed rate had the clearest practical association with R_a ; the higher-feed trials generally produced greater measured roughness.

Run 4 produced the lowest measured surface-roughness values at 1250 rpm, 300 mm/min and 0.4 mm: $R_a = 1.992 \mu\text{m}$, $R_q = 2.456 \mu\text{m}$ and $R_z = 11.101 \mu\text{m}$. It is the best observed condition among the nine trials and was not independently confirmed.

The largest calculated MRR, 6480 mm³/min, occurred in Run 3. Hence, the trial with the highest calculated removal productivity was not the one with the lowest measured roughness.

The exploratory desirability analysis likewise pointed to Run 4. Since the original project record does not retain the complete weighting information, this result is not treated as an independently validated optimization outcome.

The reported first-order R_a regression model had $R^2 = 14.3\%$; therefore, it should be used only for trend interpretation rather than high-accuracy prediction.

The identified parameter combination can therefore be regarded as a starting condition for the particular VMC 850, SS304 material, cutting tool and pocket geometry examined here. It was not confirmed independently and should not be generalized as a universal optimum.

6. Limitations and Future Work

The study is limited by the nine-run design, the lack of repeated trials and the absence of an independent confirmation experiment. The ANOVA has only two residual degrees of freedom, so the residual term provides limited information about unexplained variation and cannot serve as a pure repeatability estimate. One roughness observation was available for each condition, preventing a statistical assessment of measurement repeatability. Coolant condition, cutting force, vibration, spindle power and tool-life progression were not varied. The conclusions consequently apply to the particular SS304, VMC 850, tool and pocket configuration investigated.

A useful next stage would be replicated testing at the selected setting followed by an independent confirmation run, together with direct measurement of cutting force and spindle power and a larger experimental design. More observations would also provide a stronger basis for regression or machine-learning prediction. The framework could subsequently be extended to simultaneous consideration of surface quality, MRR, machining time, energy and machining cost. Lubrication was outside the present study, although earlier AISI 304 work indicates that lubrication strategy can influence roughness and tool wear [17].

Author Contributions: ¹Rabia Siddiqui: supervision, study planning, data analysis, result interpretation, and manuscript writing. ²Ali Zulqarnain: research journal selection, experimental planning, data analysis, and manuscript review. ³Muhammad Zaid Khan: experimental planning, data analysis, and manuscript review. ⁴Hassan Ali, ⁵Syed Ahsan Rashid, and ⁶Baseer Imran: experimentation, surface roughness measurement, and data recording. All authors reviewed and approved the final manuscript.

Conflicts of Interest: The authors declare that they have no competing interests.

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Data Availability Statement: The numerical results presented in this study are based on the experimental data obtained during the machining trials. The underlying measurement records may be obtained from the corresponding author upon reasonable request, subject to applicable institutional and project permissions.

Ethical Statement: This research was conducted in accordance with established principles of research ethics and integrity. All experimental procedures were carried out responsibly and transparently.

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Abbreviations:

AISI American Iron and Steel Institute

ANOVA Analysis of variance

DOE Design of experiments

GRA Grey relational analysis

MRR Material removal rate

RSM Response-surface methodology

S/N Signal-to-noise ratio

SS304 Stainless steel 304

TiAlN Titanium aluminum nitride

VMC Vertical machining center

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