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RESEARCH

Optimization of Cutting Fluid Concentration and Flow Rate for Surface Roughness Control in Turning of AISI 1045 Steel

Zuingli Santo Bandaso[a,*], Massriyady Massaguni[a], Zulkifli Djafar[b]

[a]*ATI Makassar Polytechnic, Department of Agro Industry Manufacturing Engineering, South Sulawesi, Indonesia,*
[b]*Hasanuddin University, Department of Mechanical Engineering, South Sulawesi, Indonesia.*

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* Corresponding author:

Zuingli Santo Bandaso
E-mail: zuinglibandaso@atim.ac.id

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A B S T R A C T

This study investigates the combined effects of soluble cutting fluid concentration and flow rate on average surface roughness (Ra) during conventional turning of AISI 1045 steel under flood-cooling conditions. Experiments were designed using a Taguchi L9 orthogonal array with four control factors: spindle speed, feed rate, cutting fluid concentration, and cutting fluid flow rate. The tested levels were 235, 530, and 880 rpm for spindle speed; 0.05, 0.10, and 0.17 mm/rev for feed rate; 1.5%, 6%, and 12% for cutting fluid concentration; and 0.15, 0.5, and 1.0 L/min for cutting fluid flow rate. Surface roughness was measured as Ra using a Mitutoyo SJ-410 portable surface roughness tester, with three readings averaged for each experimental run. The measured Ra values ranged from 1.877 to 3.627 μm. Factor contribution analysis within the investigated experimental domain showed that feed rate was the dominant parameter, accounting for 63.91% of the total Ra variation, followed by cutting fluid concentration at 15.40% and cutting fluid flow rate at 7.06%, while spindle speed contributed 0.24%. The lowest measured Ra value of 1.877 μm was obtained at 530 rpm, 0.05 mm/rev feed rate, 6% cutting fluid concentration, and 1.0 L/min flow rate; this condition represents the best observed experimental run within the tested combinations. The regression model showed good agreement with the experimental data, with R^2 = 86.61% and adjusted R^2 = 80.65%. The results indicate that surface roughness in AISI 1045 turning is primarily governed by feed-rate-controlled surface geometry, while cutting fluid concentration and flow rate provide secondary contributions through lubrication and cooling effects. Therefore, effective surface finish control requires balanced cutting fluid application rather than simply increasing coolant concentration or flow rate.

1. INTRODUCTION

Turning is one of the most widely used machining processes in metal manufacturing because of its versatility, cost-effectiveness, and capability to produce cylindrical components with acceptable dimensional accuracy. In turning operations, average surface roughness (Ra) is commonly used as a key indicator of machined surface quality because it affects contact behavior, wear resistance, fatigue performance, and tribological response. For medium-carbon steels such as American Iron and Steel Institute (AISI) 1045 steel, which is widely used for shafts, gears, and structural components, surface integrity is particularly important because these parts are often subjected to cyclic loading and sliding contact. Previous studies on AISI 1045 and steel turning have shown that surface roughness is closely related to tool wear, insert geometry, cutting conditions, and process stability, which ultimately influence component performance and service life [1-3].

In addition to surface roughness, dimensional accuracy and surface integrity during turning are strongly influenced by heat generation in the cutting zone. Cutting heat is mainly produced by plastic deformation in the primary shear zone and friction at the tool–chip and tool–workpiece interfaces. If this heat is not effectively controlled, thermal expansion of the workpiece and cutting tool may increase dimensional deviation, while high interface temperatures can accelerate tool wear and promote unstable cutting. Recent work on AISI 1045 turning has emphasized that coolant condition affects not only surface roughness but also tool wear, dimensional deviation, electric-current demand, and chip morphology, confirming the importance of thermal and tribological control in this material system [4,5].

Cutting fluids are commonly applied in turning to control temperature, friction, chip evacuation, and tool wear. Their cooling function reduces thermal loading in the cutting zone, while their lubricating function lowers frictional shear at the tool–chip and tool–workpiece interfaces. These combined effects can improve surface finish, reduce tool wear, and stabilize the machining process when the fluid reaches the active contact region effectively [6-8]. Therefore, cutting-fluid performance depends not only on fluid type or formulation but also on delivery-related variables such as flow rate, direction, and penetration into the tool–chip interface.

Despite the widespread use of flood cooling, inappropriate cutting-fluid parameters may still result in insufficient lubrication or cooling at the active cutting interfaces. A low fluid supply may fail to penetrate the tool–chip contact zone, whereas an excessive or poorly selected supply does not necessarily provide proportional improvements in surface finish. Similarly, unsuitable fluid concentration may alter the balance between lubrication and heat removal. For AISI 1045 steel, these issues are important because the generated heat and friction can affect roughness formation, tool wear, and dimensional stability during turning [4-6]. A systematic assessment of cutting-fluid concentration and flow rate is therefore required to improve process reliability without assuming that higher coolant use automatically leads to better surface quality.

Previous studies have addressed these challenges by comparing dry cutting, wet/flood cooling, and minimum quantity lubrication (MQL) strategies. For AISI 1045 turning, design-of-experiments studies have shown that lubrication strategy can influence surface roughness, cutting force, energy consumption, and tool wear [9-11]. Recent reviews and experimental studies also show that water-miscible and vegetable-oil-based cutting fluids can improve machining performance by reducing friction, heat generation, and tool wear under appropriate application conditions [8,12]. However, many studies still treat coolant condition as a broad category, such as dry, wet, or MQL, rather than examining the delivery parameters that control how the fluid acts at the cutting interface.

Among the delivery and formulation variables, cutting-fluid concentration and cutting-fluid flow rate are particularly relevant to flood turning. Cutting-fluid concentration affects the balance between lubrication and cooling: a higher oil or additive fraction may enhance boundary lubrication and reduce friction, but it may also modify heat-transfer behavior. Therefore, concentration does not necessarily produce a monotonic improvement in surface finish. Gariani et al. [12] showed that cutting-fluid concentration can be incorporated as an optimization variable together with feed rate and cutting speed when evaluating surface roughness and tool flank wear under flood turning. This supports the need to treat concentration as a controllable machining parameter rather than as a fixed background condition.

Cutting-fluid flow rate is another important parameter because it controls the quantity of fluid supplied to the cutting zone and affects the possibility of fluid penetration into the tool–chip interface. Inadequate flow may limit heat removal and lubrication, whereas excessive flow may increase fluid consumption without necessarily improving Ra. The importance of delivery conditions has been demonstrated in AISI 1045 turning, where cutting-fluid direction and flow rate affected tool life, and in recent AISI 1045 studies where coolant strategy influenced tool wear, surface roughness, and dimensional deviation [4,6]. Thus, flow rate should be considered not only as a supply quantity but also as a factor affecting tribological access to the active cutting region.

Although previous studies have examined coolant strategy, fluid direction, flow rate, or concentration in machining, the combined influence of soluble cutting-fluid concentration and flow rate on Ra in conventional flood turning of AISI 1045 steel remains insufficiently quantified. Most available AISI 1045 studies compare cooling/lubrication strategies such as dry cutting, flood cooling, or MQL, while fewer studies isolate concentration and flow rate as simultaneous controllable variables within the flood-cooling condition [6,9,10]. This creates a specific gap in understanding how concentration–flow-rate combinations affect roughness formation under practical conventional turning conditions.

Accordingly, this study investigates the effects of soluble cutting-fluid concentration and cutting-fluid flow rate on Ra during conventional straight turning of AISI 1045 steel under flood-cooling conditions. The study uses a Taguchi L9 orthogonal array to evaluate four control factors: spindle speed, feed rate, cutting-fluid concentration, and cutting-fluid flow rate. The main contribution is the focused assessment of concentration and flow rate as simultaneous coolant-related variables, while also comparing their influence with conventional cutting parameters. The Taguchi approach is employed as a factor-screening and comparative analysis method to identify the relative influence of these parameters within the selected experimental levels. The study does not assume that increasing concentration or flow rate will always reduce roughness; instead, it evaluates whether balanced coolant application can improve surface finish within the selected experimental levels. The scope is limited to Ra as the primary response, and the findings are interpreted within the investigated parameter range.

2. METHODOLOGY

2.1 Overall research flow

The present study followed a structured methodological framework to investigate the effects of soluble cutting fluid concentration and cutting fluid flow rate on average surface roughness (Ra) during the turning of AISI 1045 steel. The work began with a literature review on surface roughness formation in turning, with emphasis on feed-rate-controlled surface geometry, cutting-fluid lubrication and cooling, and cutting-fluid delivery to the tool–chip and tool–workpiece interfaces. Previous machining studies have shown that cutting-fluid application can influence thermal control, lubrication efficiency, tool wear, and surface integrity, while design of experiments (DOE) methods are useful for screening dominant machining factors when the number of experimental trials is limited [10,12,13].

Based on the literature review and the objective of evaluating coolant-related parameters, four control factors were selected: spindle speed, feed rate, soluble cutting fluid concentration, and soluble cutting fluid flow rate. Spindle speed and feed rate were included because they are conventional turning parameters that affect chip formation, cutting temperature, and feed-mark geometry. Cutting fluid concentration and flow rate were selected because they influence the balance between lubrication, cooling, and fluid penetration into the cutting zone [6,12]. The workpiece material, cutting insert, cutting fluid, and machining conditions were then selected to represent conventional turning practice for medium-carbon steel within the capability of the available machine tool.

The experimental design was developed using the Taguchi method to screen the main effects of the selected machining and cutting-fluid parameters with a limited number of experimental runs. A Taguchi L9 orthogonal array was used because four factors were investigated at three levels each. This approach was applied as a factor-screening and contribution-analysis method within the investigated experimental domain; however, because each machining condition was performed once, the design does not provide independent machining replications for confirmatory statistical inference. After the design stage, turning experiments were conducted on a conventional lathe under flood-cooling conditions. The resulting Ra data were analyzed using signal-to-noise (S/N) ratio analysis, analysis of variance (ANOVA), regression modeling, and interaction plots to evaluate factor trends and relative contributions within the investigated experimental range [10,13].

2.2 Materials and apparatus

The workpiece material used in this investigation was AISI 1045 medium-carbon steel, selected because of its wide industrial application and sensitivity to thermal and tribological conditions during machining. Cylindrical bars with a diameter of 40 mm and a total length of 400 mm were used for the experimental trials. Before machining, the workpieces were aligned to maintain concentricity and stable clamping during turning. To provide separate machined segments for the experimental runs, circumferential grooves with a depth of 5 mm were produced along the workpiece, as shown in Fig. 1. The distance between adjacent grooves was 40 mm. This segmentation allowed the surface roughness of each run to be measured on its corresponding machined segment; however, these segments should not be interpreted as independent machining replications. The AISI 1045 steel was used as supplied by the material provider, and no additional heat treatment was performed by the authors before machining. However, the prior heat-treatment history and initial microstructure of the supplied material were not documented; therefore, this limitation is acknowledged in interpreting the machining response.

Shell Dromus B / DROMUS® B water-miscible soluble oil was used as the cutting fluid throughout the experiments. The fluid was prepared by mixing soluble oil with water at three concentration levels: 1.5%, 6%, and 12% by volume. These levels were selected to represent low, intermediate, and relatively high soluble-oil contents so that the effect of concentration on Ra could be evaluated under flood-cooling conditions. Water-miscible cutting fluids are commonly used because they provide combined cooling and lubrication, but their effectiveness depends on the balance between heat removal, boundary lubrication, and access to the cutting interface [8,12]. The viscosity, pH, and in-process temperature of the cutting fluid at each concentration were not directly measured in this study; therefore, their possible influence on cooling and lubrication performance is acknowledged as a methodological limitation.

Fig. 1. Segmented AISI 1045 steel workpiece showing circumferential grooves used to separate the machined sections for surface roughness measurement.

All turning experiments were conducted on a conventional engine lathe equipped with a recirculating cutting-fluid system and an electric pump to provide continuous fluid supply to the cutting zone. The cutting tool was a WNMG 080404 carbide insert with chemical vapor deposition (CVD) coating and a nose radius of 0.4 mm; this corrects the earlier incorrect description of the insert as CNMG-type. The tool overhang was fixed at 30 mm to reduce tool deflection and vibration, which can influence surface roughness. The depth of cut was kept constant at 0.5 mm for all experimental runs. To reduce the possible influence of progressive tool wear on Ra, the insert was replaced periodically during the experiments. However, flank wear was not quantitatively measured; therefore, the possible effect of tool wear progression is acknowledged as a methodological limitation.

Surface roughness was measured using a Mitutoyo SJ-410 portable surface roughness tester, as shown in Fig. 2. The measured parameter was average surface roughness (Ra). The instrument was operated using the ISO 1997 evaluation setting, roughness profile mode (R), and Gaussian filter. The short-wavelength cutoff, λs, was 2.5 μm, and the cutoff length, λc, was 0.8 mm. Five sampling lengths were used (N = 5), resulting in an evaluation length of 4.0 mm. Measurements were performed along the axial direction of the cylindrical workpiece, parallel to both the workpiece axis and the tool feed direction. For each experimental run, three Ra measurements were taken at different circumferential positions on the same machined segment, and their average was used as the representative response. These repeated measurements were used only to reduce measurement variability and were not treated as independent machining replications for statistical inference. Before measurement, the tester was calibrated according to the manufacturer's procedure.

Fig. 2. Experimental setup for surface roughness measurement using a Mitutoyo SJ-410 portable surface roughness tester.

2.3 Experimental setup and design

Straight turning operations were performed under flood-cooling conditions, in which the cutting fluid was continuously supplied to the cutting zone during each experimental run. Cutting fluid flow rate was selected as a coolant-delivery variable and was varied at three levels: 0.15, 0.5, and 1.0 L/min. These levels were used to represent low, intermediate, and relatively high delivery conditions, allowing the effect of coolant supply on lubrication, heat removal, and possible fluid access to the tool–chip interface to be evaluated. Cutting-fluid direction and flow rate have been shown to influence tool life in finish turning of AISI 1045 steel by affecting fluid penetration into the tool–workpiece and tool–chip contact regions [6]. In addition to the cutting-fluid variables, spindle speed and feed rate were varied at three levels: 235, 530, and 880 rpm for spindle speed, and 0.05, 0.10, and 0.17 mm/rev for feed rate. These levels were selected within the capability of the conventional lathe and to represent practical operating conditions for turning AISI 1045 steel. Feed rate was included because it directly controls feed-mark geometry and undeformed chip thickness, both of which strongly influence Ra formation. Spindle speed was included because it affects cutting temperature, chip formation, and contact conditions at the tool–workpiece interface. Similar design-of-experiments studies on AISI 1045 turning have treated feed rate, cutting speed/spindle speed, tool geometry, and coolant/lubrication conditions as important factors affecting surface roughness and cutting force [10,13].

To reduce workpiece deflection and chatter during machining, the free end of the workpiece was supported by a live center mounted on the tailstock. This arrangement helped maintain stable cutting conditions and reduced the possibility of vibration-induced surface irregularities. All machining trials were conducted with a constant depth of cut of 0.5 mm and the same WNMG 080404 chemical vapor deposition (CVD)-coated carbide insert geometry. The insert nose radius was 0.4 mm, and the tool overhang was maintained at 30 mm, as described in Section 2.2. These parameters were kept constant so that the effects of spindle speed, feed rate, cutting fluid concentration, and cutting fluid flow rate could be evaluated more clearly.

The experiments were designed using a Taguchi L9 (3^4) orthogonal array, as shown in Table 2. Four control factors were included: spindle speed (A), feed rate (B), cutting fluid concentration (C), and cutting fluid flow rate (D), with each factor assigned three levels, as summarized in Table 1. The L9 array was selected to screen the main effects and relative influence of the four factors while limiting the experimental matrix to nine runs. Similar Taguchi-based approaches have been used for surface roughness analysis and multi-response optimization in turning of AISI 1045 steel and related machining studies [13,14]. However, the L9 design used here was applied as a screening design and was not intended to establish a fully validated optimum condition or to fully resolve higher-order interactions and nonlinear response curvature.

Table 1. Control factors and levels used in the Taguchi experimental design factor.

Factor	Level 1	Level 2	Level 3
SpindleSpeed (A) (rpm)	235	530	880
Feed Rate (B) (mm/rev)	0.05	0.1	0.17
Soluble Cutting Fluid Concentration (C) (%)	1.5	6	12
Soluble Cutting Fluid Flow rate (D) (L/min)	0.15	0.5	1

Each experimental condition in the L9 array was machined once. After each turning pass, surface roughness was measured on the corresponding segmented section of the workpiece. For each run, three Ra measurements were taken at different circumferential positions on the same machined segment, and the average value was used as the representative response. These repeated readings were used to reduce local measurement variability; however, they do not constitute independent machining replications. Therefore, the subsequent statistical analysis should be interpreted as a main-effect screening and factor-contribution analysis within the tested parameter range. The averaged Ra data were analyzed using signal-to-noise (S/N) ratio analysis, analysis of variance (ANOVA), regression modeling, and interaction plots. The absence of independent machining replications and confirmation experiments is acknowledged as a limitation, and future work should include repeated machining trials and confirmation runs at the predicted optimum condition.

Table 2. Taguchi L9 (3^4) orthogonal array matrix.

Run	Spindle Speed (A)	Feed Rate (B)	Soluble Cutting Fluid Concentration (C)	Soluble Cutting Fluid Flow rate (D)
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

3. RESULTS

3.1 Surface roughness characteristics

3.1.1 Surface roughness measurement

The turning experiments conducted on AISI 1045 steel under conventional flood-cooling conditions produced average surface roughness (Ra) values ranging from 1.877 to 3.627 µm, as summarized in Table 3. The lowest Ra value was obtained in Run 4, whereas the highest average Ra value was obtained in Run 8. This range indicates that surface roughness was affected by the combined influence of cutting parameters and cutting-fluid conditions within the tested levels. The observed Ra variation is consistent with turning studies showing that surface finish is controlled primarily by feed-related surface geometry, while cooling and lubrication conditions can modify friction, heat generation, and tool wear behavior [1,2,5].

Table 3. Surface roughness measurement results for the Taguchi L9 experimental runs.

Run	Spindle Speed, A (Rpm)	Feed, B (mm/rev)	Soluble Cutting Fluid, C (%)	Soluble Cutting Fluid Flow rate, D (L/min)	Ra1 (µm)	Ra2 (µm)	Ra3 (µm)	Average Ra (µm)
1	235	0.05	1.5	0.15	2.603	2.296	2.747	2.549
2	235	0.1	6	0.5	2.954	2.515	2.803	2.757
3	235	0.17	12	1	3.050	3.260	3.570	3.293
4	530	0.05	6	1	2.246	1.586	1.799	1.877
5	530	0.1	12	0.15	3.307	3.459	3.640	3.469
6	530	0.17	1.5	0.5	2.920	2.800	2.900	2.873
7	880	0.05	12	0.5	2.120	2.269	2.323	2.237
8	880	0.1	1.5	1	3.650	3.680	3.550	3.627
9	880	0.17	6	0.15	2.621	2.740	2.901	2.754

The minimum average surface roughness of 1.877 µm was achieved in Run 4 at a spindle speed of 530 rpm, feed rate of 0.05 mm/rev, cutting fluid concentration of 6%, and cutting fluid flow rate of 1.0 L/min. The result suggests that the lowest tested feed rate was favorable for surface finish because a lower feed rate reduces the theoretical feed-mark height and decreases the geometric contribution to Ra. Under this condition, the intermediate cutting fluid concentration and high flow rate may also have supported lubrication and heat removal at the cutting interface; however, this interpretation represents a possible mechanism inferred from the measured Ra response and should not be considered as direct evidence because cutting temperature, fluid penetration, and tool wear were not directly measured.

In contrast, the highest average Ra value of 3.627 µm was recorded in Run 8 at 880 rpm, 0.10 mm/rev feed rate, 1.5% cutting fluid concentration, and 1.0 L/min flow rate. Run 5 also produced a high Ra value of 3.469 µm at 530 rpm, 0.10 mm/rev feed rate, 12% concentration, and 0.15 L/min flow rate. These results show that surface roughness did not vary monotonically with any single parameter, which is expected in a Taguchi L9 design involving multiple factors. The factor-ranking results indicate that feed rate had the largest influence on Ra variation within the investigated experimental domain. Mechanistically, feed rate directly affects the feed-mark spacing and theoretical surface profile height, while higher undeformed chip thickness can increase cutting forces and vibration tendency. Similar conclusions on the dominant role of feed rate in turning surface roughness have been reported for AISI 1045 and related steels [2,3,13].

Compared with feed rate, spindle speed produced a smaller apparent effect on Ra within the investigated range. Changes in spindle speed may influence chip formation, cutting temperature, and tool–workpiece contact conditions, but the present results indicate that these effects were secondary to the geometric influence of feed rate. Cutting fluid concentration and flow rate also affected Ra, most likely by modifying the balance between lubrication, cooling, and fluid access to the cutting interface. The lowest measured Ra was obtained at 6% concentration and 1.0 L/min flow rate; however, this combination represents the best observed experimental condition within the tested runs rather than a confirmed optimum condition. Because cutting temperature, fluid penetration, and tool wear were not directly measured, the lubrication and cooling explanation is presented as a mechanism supported by machining literature rather than as directly measured evidence [4,7,12].

3.2 Statistical analysis of machining parameters

3.2.1 Signal-to-noise ratio analysis

Taguchi signal-to-noise (S/N) ratio analysis was performed using the smaller-the-better criterion because lower Ra values indicate better surface finish. The S/N ratio was used to identify factor levels associated with lower roughness within the tested Taguchi L9 experimental domain. However, because the machining trials were not independently replicated, the S/N analysis should be interpreted as a parameter-screening tool rather than as full confirmation of process robustness. Similar Taguchi-based studies on AISI 1045 turning have used S/N ratio analysis to evaluate surface roughness and related machining responses [4,13]. The main-effects plot of the S/N ratios for Ra is presented in Fig. 3.

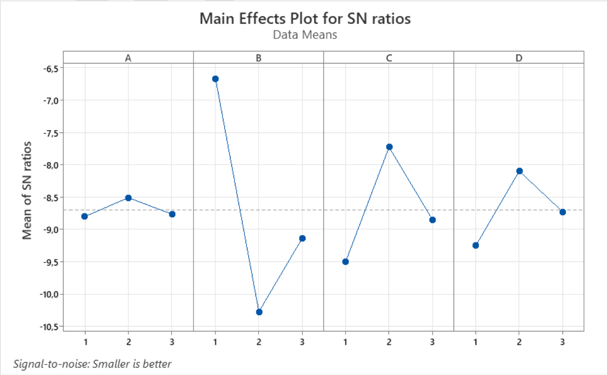

Fig. 3. Main-effects plot of the signal-to-noise (S/N) ratios for average surface roughness (Ra) based on the smaller-the-better criterion.

The S/N response indicates that feed rate, Factor B, had the largest delta value among the investigated factors, ranking it as the most influential parameter affecting Ra within the tested factor range. This result is physically consistent with turning mechanics because feed rate governs feed-mark spacing and theoretical surface profile height. Cutting fluid concentration, Factor C, ranked second, followed by cutting fluid flow rate, Factor D, suggesting that coolant formulation and delivery influenced Ra as secondary factors. Spindle speed, Factor A, showed the smallest delta value, indicating a limited effect on Ra within the tested range.

The S/N ratio trends indicate that the preferred levels for minimizing Ra within the tested factor range correspond to a low feed rate, intermediate cutting fluid concentration, and intermediate cutting fluid flow rate. Based on the Taguchi response, the preferred flow-rate level was 0.5

L/min. However, this result should be distinguished from the minimum measured Ra, which occurred in Run 4 at a flow rate of 1.0 L/min. The S/N ratio represents the average response trend of each factor level across the L9 design, whereas the minimum Ra reflects one specific experimental combination. The preferred Taguchi factor-level combination was A2-B1-C2-D2, corresponding to 530 rpm spindle speed, 0.05 mm/rev feed rate, 6% cutting-fluid concentration, and 0.5 L/min flow rate. This combination represents a preferred parameter-level setting based on the S/N response and should not be considered a validated optimum without confirmation experiments. Therefore, the Taguchi analysis identifies preferred factor levels within the investigated design space but does not establish a validated optimum condition without confirmation experiments.

3.2.2 Analysis of variance (ANOVA)

Analysis of variance (ANOVA) was conducted to evaluate the relative influence of each machining parameter on Ra and to estimate the contribution of each factor within the tested experimental domain. The S/N ratio analysis, ANOVA, regression modeling, and interaction plots were performed using Minitab 21. The ANOVA results for Ra are summarized in Table 4. Because each machining condition was conducted once and the three Ra measurements represented repeated measurements from the same machined segment rather than independent machining replications, the ANOVA results are interpreted as factor-ranking and contribution-analysis evidence within the investigated domain rather than as confirmatory statistical significance testing.

Table 4. Analysis of variance for average surface roughness (Ra).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
A: Spindle Speed	2	0.02177	0.01088	0.16	0.854
B:Feed Rate	2	5.87203	2.93601	42.95	0.000
C:Cutting Fluid Concentration	2	1.41512	0.70756	10.35	0.001
D: Cutting fluid flow rate	2	0.64854	0.32427	4.74	0.022
Error	18	1.23058	0.06837		
Total	26	9.18804			

Note: F-values and P-values are reported for transparency but are not interpreted as confirmatory evidence of statistical significance because the machining conditions were not independently replicated.

Feed rate showed the largest adjusted sum of squares among the investigated factors, indicating that it was the dominant factor influencing Ra within the tested conditions. This observation agrees with the physical role of feed rate in generating the feed marks that form the turned surface profile. Cutting fluid concentration and flow rate also showed measurable contributions to surface roughness variation, although their effects were secondary compared with feed rate. These secondary effects are plausibly related to changes in lubrication at the tool–chip and tool–workpiece interfaces, heat removal, built-up edge tendency, and tool wear progression. However, because cutting temperature, built-up edge, and flank wear were not directly measured, these mechanisms should be interpreted as literature-supported explanations rather than direct observations from this study [5,7,12].

3.2.3 Percentage contribution of machining parameters

The relative influence of each machining parameter was further quantified through percentage contribution analysis derived from the ANOVA adjusted sums of squares. The contribution values were recalculated using the total sum of squares as the reference, including the residual error contribution. As shown in Fig. 4 and Table 5, feed rate contributed 63.91% of the total Ra variation, indicating that feed rate was the dominant factor within the investigated range. Cutting fluid concentration contributed 15.40%, followed by cutting fluid flow rate at 7.06%, whereas spindle speed contributed 0.24%. The residual error contribution was 13.39%, representing the unexplained variation within the analyzed dataset. These results indicate that surface roughness was primarily governed by feed-rate-controlled surface geometry, while cutting fluid concentration and flow rate acted as secondary factors affecting lubrication and cooling conditions.

Table 5. Percentage contribution of machining parameters to average surface roughness (Ra) based on total sum of squares.

Source	Sum of Squares	Contribution (%)
A: Spindle speed	0.02177	0.24
B: Feed rate	5.87203	63.91
C: Cutting fluid concentration	1.41512	15.40
D: Cutting fluid flow rate	0.64854	7.06
Error	1.23058	13.39
Total	9.18804	100.00

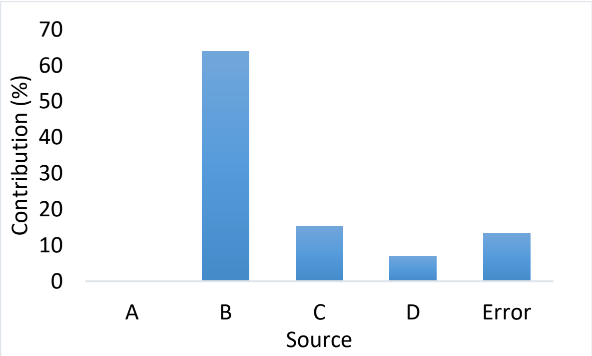

Fig. 4. Percentage contribution of spindle speed, feed rate, cutting fluid concentration, cutting fluid flow rate, and error contribution to average surface roughness (Ra), calculated using the ANOVA adjusted sum of squares relative to the total sum of squares.

The dominance of feed rate is consistent with previous turning studies in which feed rate strongly influenced the generated surface profile and Ra values [2,3,13]. However, the percentage contributions reported here should be interpreted within the selected Taguchi L9 factor levels and the available experimental dataset. Because the machining runs were not independently replicated, these contribution values should be considered as indicators of relative factor influence within the tested design space rather than generalized variance estimates for all AISI 1045 turning conditions.

3.3 Regression analysis and model adequacy

3.3.1 Regression model

To describe the relationship between Ra and the investigated machining parameters, a general linear regression model was developed using the experimental data. The model in Eq. (1) relates Ra to the coded factor levels of spindle speed (A), feed rate (B), cutting fluid concentration (C), and cutting fluid flow rate (D). The model should therefore be used only for prediction within the tested factor levels and should not be extrapolated beyond the experimental domain.

$$Ra = 2.7656 - 0.0136A_1 - 0.0259A_2 + 0.0395A_3 - 0.6121B_1 + 0.5186B_2 + 0.0935B_3 + 0.2506C_1 - 0.3028C_2 + 0.0522C_3 + 0.1582D_1 - 0.2105D_2 + 0.0523D_3 \qquad (1)$$

where Ra is the predicted average surface roughness; A_1–A_3, B_1–B_3, C_1–C_3, and D_1–D_3 are coded level indicators for spindle speed, feed rate, cutting fluid concentration, and cutting fluid flow rate, respectively.

The regression model yielded a coefficient of determination of R^2 = 86.61% and an adjusted R^2 = 80.65%, indicating that the model explained a substantial portion of the Ra variation within the experimental dataset. Among the coded coefficients, the feed-rate terms showed the largest magnitudes, which is consistent with the factor-ranking results and the established geometric role of feed rate in surface profile formation during turning [2,3,13]. However, because the dataset was obtained from a Taguchi L9 design without independent machining replications, the model should be interpreted as an empirical approximation within the investigated parameter range rather than as a fully validated predictive model.

More advanced approaches, such as response surface methodology (RSM), artificial neural networks, and machine-learning models, can capture nonlinear effects and complex interactions more comprehensively when larger datasets are available [12,15]. Nevertheless, the present coded regression model provides an interpretable first-order approximation of Ra behavior within the selected factor levels. Future work should consider RSM or data-driven modeling combined with replicated experiments and confirmation trials to improve prediction reliability.

3.3.2 Model validation

The adequacy of the developed regression model was evaluated using residual analysis. The normal probability plot of residuals, shown in Fig. 5, indicates that the residuals approximately follow the reference line, suggesting acceptable agreement between the residual distribution and the assumptions of the fitted model.

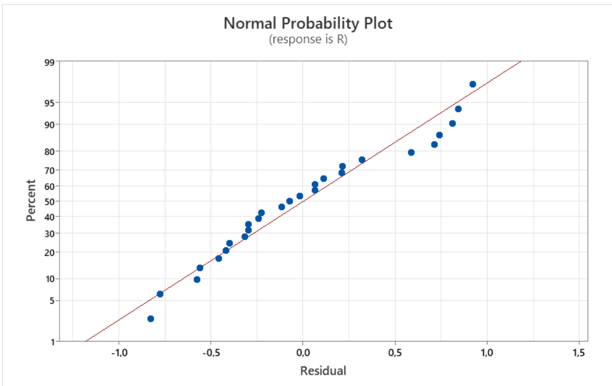

Fig. 5. Normal probability plot of residuals for the regression model of average surface roughness (Ra).

Residual inspection also provides a useful check for systematic deviations between measured and predicted Ra values. However, residual analysis represents a diagnostic evaluation of model behavior and does not replace independent machining replication or confirmation experiments. Therefore, the model reliability is interpreted only within the investigated parameter space and the available dataset.

Although the R^2, adjusted R^2, and residual plot support the descriptive capability of the fitted model within the available data, an independent confirmation experiment was not conducted. This limitation is acknowledged because confirmation trials are commonly used in Taguchi-based optimization studies to verify predicted parameter combinations and quantify prediction error [13,14]. Future work should include confirmation runs at the predicted parameter combination and report the prediction error between measured and predicted Ra values.

3.4 Interaction effects

Possible interaction tendencies among machining parameters were examined visually using interaction plots, as shown in Fig. 6. The plots suggest that the effects of cutting fluid concentration and flow rate on Ra may vary with feed rate within the tested parameter range. At lower feed rates, changes in cutting-fluid conditions appear to produce clearer differences in Ra, possibly because the geometric contribution of feed is smaller and lubrication or cooling effects may become relatively more apparent. This interpretation is consistent with the role of cutting fluids in reducing friction and heat generation at the tool–chip and tool–workpiece interfaces [7,12]. However, because interaction terms were not included in the statistical model and were not independently validated, these trends should be interpreted only as visual indications rather than confirmed interaction effects.

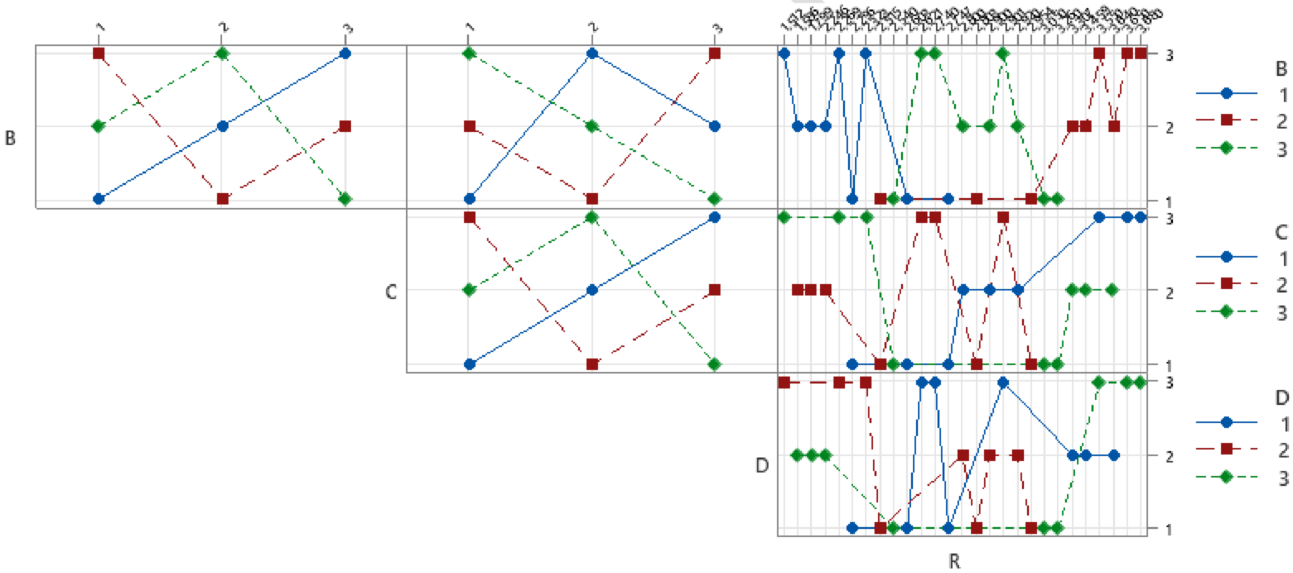

Fig. 6. Interaction plot showing the combined effects of feed rate, cutting fluid concentration, and cutting fluid flow rate on average surface roughness (Ra).

At higher feed rates, the influence of cutting-fluid-related parameters appears to diminish because Ra becomes increasingly controlled by feed-driven surface geometry. Higher feed rates increase feed-mark spacing and theoretical profile height, which can mask smaller improvements associated with lubrication and cooling. In this condition, even if the cutting fluid improves heat removal or reduces friction, the geometric contribution of feed may remain the dominant source of roughness. This interpretation represents a mechanistic explanation of the observed trend and should be considered within the tested experimental range. This explanation is consistent with studies showing that feed rate is often the strongest factor governing Ra in turning, while coolant conditions tend to act as secondary or moderating factors [3,12,13].

Overall, the interaction plots suggest that feed rate remains the primary determinant of Ra, while cutting fluid concentration and flow rate may modify Ra under selected cutting conditions. Because the Taguchi L9 design used in this study was primarily a main-effect screening design, the interaction results should be used to guide interpretation rather than to claim statistically significant interactions. Future studies using replicated experiments or response surface methodology should be conducted to quantify concentration–flow-rate interactions more rigorously.

4. DISCUSSION

The results provide an empirical basis for interpreting how machining parameters and cutting-fluid application influence average surface roughness (Ra) during conventional turning of AISI 1045 steel. The dominance of feed rate is consistent with turning mechanics because feed rate directly determines feed-mark spacing and theoretical surface profile height. In the present study, feed rate accounted for 63.91% of the total Ra variation based on the corrected contribution calculation using the total sum of squares, indicating that roughness formation was primarily governed by feed-rate-controlled surface geometry within the tested parameter range. This finding agrees with previous AISI 1045 and steel-turning studies in which feed rate was identified as a major contributor to surface roughness [2,3,13]. However, because the Taguchi L9 design was not independently replicated, this conclusion should be interpreted as a factor-ranking result within the investigated experimental domain rather than as a fully generalized statistical claim.

The small contribution of spindle speed, 0.24%, indicates that its influence on Ra was limited within the investigated range of 235–880 rpm. Unlike feed rate, spindle speed does not directly define the theoretical feed-mark height. Instead, it may influence Ra indirectly through chip formation, contact time, cutting temperature, and frictional conditions at the tool–chip and tool–workpiece interfaces. Within the present experimental window, these indirect effects were not large enough to overcome the dominant feed-rate contribution. This interpretation is consistent with previous studies showing that speed effects may become more pronounced only under specific cutting regimes, tool-wear states, or cooling/lubrication conditions [1,2].

In contrast to the dominant geometric effect of feed rate, cutting fluid concentration and cutting fluid flow rate showed secondary contributions to Ra variation within the investigated parameter range. Their corrected contributions were 15.40% and 7.06%, respectively. These results indicate that coolant-related parameters did not override the surface profile imposed by feed rate, but they influenced Ra by modifying tribological and thermal conditions at the cutting interfaces. In practical terms, concentration and flow rate may affect boundary lubrication, heat removal, chip evacuation, and the tendency for built-up edge formation. Because cutting temperature, built-up edge, and flank wear were not directly measured, these mechanisms are interpreted as literature-supported explanations rather than direct observations from the present experiment [5,7,12].

The influence of cutting fluid concentration can be explained by the balance between lubrication and cooling. A higher soluble-oil content may improve boundary lubrication at the tool–chip and tool–workpiece interfaces, thereby reducing frictional shear and stabilizing chip formation. However, increasing concentration does not necessarily produce a monotonic improvement in Ra because changes in oil content may also alter heat-removal behavior and fluid access to the cutting zone. In this study, the lowest Ra was obtained at the intermediate concentration level of 6%, whereas the 12% level did not consistently produce the best surface finish. This observation indicates that the investigated concentration range should be selected based on performance balance rather than assuming that increasing soluble-oil fraction will always improve surface quality. Similar concentration-dependent behavior has been reported in flood turning studies where cutting fluid concentration affected surface roughness and tool flank wear [12]. The viscosity and pH of the cutting fluid at each concentration were not measured; therefore, their possible influence cannot be quantified in the present study.

Cutting fluid flow rate plays a complementary role by controlling the amount of fluid supplied to the cutting zone and the likelihood of fluid access to the tool–chip interface. In flood cooling, insufficient flow may reduce cooling and lubrication because the chip can obstruct fluid penetration into the contact region. Conversely, increasing flow rate does not always guarantee proportional improvement in

Ra because surface roughness may still be dominated by feed-rate geometry. In the present study, flow rate contributed 7.06% to Ra variation, indicating a measurable but secondary influence within the tested conditions. This finding agrees with previous AISI 1045 turning work showing that cutting-fluid direction and flow rate can influence tool life and machining performance [4,6]. Since cutting-zone fluid penetration was not directly observed, the proposed penetration mechanism should be considered an interpretation based on surface roughness trends and prior machining literature.

The interaction plots suggest that the influence of cutting fluid concentration and flow rate on Ra depends partly on feed rate. At lower feed rates, the geometric contribution to surface roughness is smaller, so changes in lubrication and cooling conditions may become more visible in the measured Ra response. At higher feed rates, the larger feed-mark spacing and increased undeformed chip thickness can dominate surface formation and mask smaller benefits associated with coolant application. Thus, the observed interaction tendency is physically reasonable: cutting fluids may improve frictional and thermal conditions, but they cannot fully compensate for roughness generated by an unfavorable feed-rate setting. However, because interaction terms were not statistically tested in the ANOVA or regression model, these results should be described as visual tendencies rather than statistically confirmed interactions.

From an industrial perspective, the findings indicate that cutting-fluid strategy should be integrated with machining-parameter selection rather than considered separately. Feed rate remains the primary control factor for Ra, especially in finishing operations, but the selection of cutting fluid concentration and flow rate can support surface-quality control by improving lubrication and heat removal. This is important because coolant application can also influence tool wear, dimensional deviation, chip formation, energy consumption, and production stability in AISI 1045 turning [4,5,11]. Therefore, practical parameter selection should emphasize balanced coolant concentration and delivery rather than assuming that higher coolant usage alone will produce improved surface quality.

Several methodological limitations must be acknowledged. First, the Taguchi L9 orthogonal array enabled efficient main-effect screening, but it was based on discrete factor levels and was not designed to fully resolve nonlinear curvature or higher-order interactions. Second, each machining condition was conducted once; the three Ra readings were repeated roughness measurements on the same machined segment and should not be interpreted as independent machining replications. Third, no independent confirmation experiment was conducted to verify the predicted parameter combination identified from the Taguchi analysis. Fourth, cutting temperature, cutting-zone fluid penetration, built-up edge formation, and quantitative flank wear were not directly measured. Therefore, the mechanisms discussed above are inferred from Ra trends, statistical results, and supporting literature, and the findings should be interpreted within the tested experimental domain.

These limitations provide clear directions for future research. Further studies should include independent machining replications and confirmation trials at the predicted parameter combination to quantify prediction error and improve statistical confidence. Response surface methodology (RSM) or other expanded design of experiments (DOE) approaches could be used to evaluate nonlinear concentration–flow-rate effects and statistically test interaction terms. Future work should also include direct measurement of cutting temperature, quantitative flank wear, tool-condition monitoring, and coolant-property characterization, including viscosity and pH, where appropriate. Extending the comparison to minimum quantity lubrication (MQL), hybrid cooling, or other sustainable lubrication strategies would improve generalizability and support multi-criteria optimization of surface roughness, tool life, dimensional stability, productivity, and sustainability in AISI 1045 turning [5,9,16].

5. CONCLUSION

This study investigated the effects of soluble cutting fluid concentration and cutting fluid flow rate on average surface roughness (Ra) during conventional flood-cooled turning of AISI 1045 steel. Using a Taguchi L9 orthogonal array, the Ra values obtained from the nine experimental runs ranged from 1.877 to 3.627 µm. The factor contribution analysis showed that feed rate was the dominant parameter, accounting for 63.91% of the total Ra variation within the investigated experimental domain. This result indicates that surface roughness formation in the present study was primarily governed by feed-rate-controlled surface geometry. Cutting fluid concentration and cutting fluid flow rate contributed 15.40% and 7.06%, respectively, while spindle speed contributed 0.24%, indicating secondary influences within the tested parameter range. These findings indicate that cutting-fluid parameters can support surface finish control through lubrication and cooling effects, but they do not override the dominant geometric influence of feed rate.

The lowest Ra value of 1.877 µm was obtained at 530 rpm spindle speed, 0.05 mm/rev feed rate, 6% cutting fluid concentration, and 1.0 L/min cutting fluid flow rate. This condition represents the best observed experimental run within the tested Taguchi L9 combinations and should not be considered a confirmed optimum condition because no independent confirmation experiment was conducted. The regression model explained a substantial portion of the experimental variation, with R^2 = 86.61% and adjusted R^2 = 80.65%. However, the model should be interpreted only within the tested factor levels. The interaction plots suggested that cutting-fluid effects were more visible at lower feed rates, where lubrication and cooling may influence surface formation more effectively; at higher feed rates, feed-driven geometric roughness tended to mask coolant-related improvements. Because interaction terms were not statistically tested, these interaction results should be interpreted as visual tendencies rather than confirmed statistical interactions.

The main contribution of this study is the focused evaluation of cutting fluid concentration and flow rate as simultaneous coolant-related variables in conventional turning of AISI 1045 steel. Practically, the results suggest that surface finish improvement should prioritize feed-rate control while also selecting an appropriate cutting fluid concentration and flow rate to support lubrication, heat removal, and cutting stability. The study is limited by the use of discrete Taguchi L9 factor levels, the absence of independent machining replications, and the absence of a confirmation experiment to verify the predicted parameter combination.

In addition, cutting temperature, cutting-zone fluid penetration, built-up edge formation, quantitative flank wear, cutting fluid viscosity, and cutting fluid pH were not directly measured. Future work should include replicated machining trials, confirmation experiments, prediction-error analysis, quantitative flank wear measurement, cutting-temperature measurement, and coolant-property characterization. Expanded response surface methodology or other design-of-experiments approaches should also be used to evaluate nonlinear concentration–flow-rate effects and statistically quantify interaction terms across wider lubrication strategies, including minimum quantity lubrication and hybrid cooling.

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