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TAGUCHI-BASED OPTIMIZATION OF MILLING PARAMETERS FOR EN24 STEEL: EXPERIMENTAL ANALYSIS OF MATERIAL REMOVAL RATE AND SURFACE ROUGHNESS

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EN24 alloy steel is widely used in high-strength engineering components such as shafts, gears and spindles, where machining performance and surface integrity are critical for reliable service. The present work investigates the influence of spindle speed, feed rate and depth of cut on material removal rate (MRR) and surface roughness (*Ra*) during milling of EN24 steel. A Taguchi L27 orthogonal array is employed to design the experiments, and three replications are carried out for each condition. Signal-to-noise ratio analysis and analysis of variance (ANOVA) are used to identify the most significant cutting parameters for both responses. The results indicate that depth of cut is the dominant factor for MRR, contributing more than 80% of the total variation, whereas feed rate is the most influential parameter for *Ra*. Regression models are developed to predict MRR and *Ra* as functions of the cutting parameters, and confirmation experiments are performed at the optimal settings. For MRR, the optimum combination of $600\ rpm$ spindle speed, $118\ mm/min$ feed rate and $0.5\ mm$ depth of cut yields a prediction error below 1%, while for *Ra* the optimal condition of $600\ rpm$, $102\ mm/min$ and $0.1\ mm$ results in a prediction error of about 2%. The study demonstrates that the Taguchi approach provides an effective and economical framework for optimising metal machining of EN24 steel, enabling higher productivity with controlled surface roughness, and contributes to improved, more sustainable manufacturing practice.

Key words: Taguchi method, analysis of variance (ANOVA), EN24 steel, milling process.

1. Introduction

Optimizing milling parameters to balance productivity and surface integrity remains a central research focus and Taguchi DOE is among the most widely used frameworks because it delivers robust settings with a limited number of trials. In end milling of difficult alloys (e.g., NiTi), Taguchi-based S/N analysis and ANOVA have repeatedly shown how spindle speed, feed rate, and depth of cut influence surface roughness and tool wear under uncontrolled noise factors, yielding repeatable parameter-selection workflows [1]. This makes Taguchi particularly suitable for a vertical turret milling (VTM) environment, where setup variation and fixture compliance can otherwise obscure true main effects.

Recent work extends classic orthogonal arrays by combining DOE with faster search and decision tools. Definitive Screening Designs (DSDs) help screen many factors efficiently and then down-select candidate parameter zones using multi-criteria decision-making, maintaining experimental discipline while reducing iteration time [2]. Evidence from high-speed machining (e.g., titanium alloys) reinforces the multi-objective structure of the problem: feed per tooth typically dominates roughness trends, while depth of cut and cutting speed largely control MRR, cycle time, and thermal load-useful priors when formulating hypotheses for hardened steels such as EN-31 [3]. Taguchi applied to compliant work pieces (e.g., thin-walled aluminium) further highlights that when clamping and toolpath are controlled, robust speed-feed combinations can improve *Ra* without severe MRR penalties, while depth of cut remains the primary lever for volumetric removal [4].

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Sustainability-oriented studies add that energy per unit volume can be co-optimized with finish via moderate tuning of speed and feed, expanding "optimality" beyond roughness alone toward shop-floor practicality [5].

Hybrid optimization pipelines are increasingly common. Local deterministic refinement (e.g., Nelder-Mead simplex) can be applied around a Taguchi-suggested neighbourhood using fitted response models, providing a practical "last-mile" improvement when the response surface is smooth but mildly nonlinear [6]. Process-assistance methods (e.g., $scCO_2$-assisted MQL with ultrasonic vibration) show that improved interface control can shift feasible operating windows toward higher throughput at comparable roughness, implying that Taguchi optima may move when cooling/lubrication conditions change [7]. Data-driven and Pareto-aware methods-such as ANN models combined with Edgeworth-Pareto ranking or RSM-GA-consistently emphasize the same trade-off structure: treat *Ra* as "smaller-is-better" and MRR as "larger-is-better," then rank compromise solutions using a transparent decision rule suitable for shop instructions [8-9].

For DOE conclusions to remain interpretable on flexible platforms like VTM, dynamics must be controlled. Stability-lobe and chatter-avoidance guidance suggests pre-filtering candidate speed/chip-load regions so that Taguchi S/N outcomes are not confounded by self-excited vibration, improving repeatability and reducing roughness scatter [10]. Mechanistic relations linking cutting speed, feed, and engagement help translate factor levels into physical chip-load quantities, allowing MRR claims and ANOVA contributions to be interpreted in process terms rather than purely statistical ones [11].

Closer to the target material class, Taguchi templates reported for EN-series steels provide practical patterns for factor-level selection, S/N objective definitions (*Ra*: smaller-is-better; MRR: larger-is-better), and ANOVA-based contribution ranking; EN-24 studies also link parameter effects to surface-integrity mechanisms, strengthening the rationale behind recommended settings [12-13]. Evolutionary Pareto methods (e.g., improved NSGA-II) and DOE-trained neural predictors offer complementary validation routes: construct a Pareto set, and then use a decision-maker criterion to select the final compromise and verify via confirmation experiments [14-16]. Finally, controlling engagement mode (up- vs. down-milling) across trials is an important experimental safeguard, since it measurably affects forces, stability, and roughness; fixing it improves effect attribution in S/N and ANOVA [17]. Overall, the literature supports a practical workflow for EN-31 on VTM: stability-screen the operating window, run a compact Taguchi DOE, apply S/N and ANOVA for factor ranking, and use a simple multi-criteria ranker (e.g., GRA/TOPSIS/COCOSO) to produce a single shop-floor setting validated by confirmation tests [18]. These studies show that using a planned experiment method (DOE) with statistical analysis helps choose the best process settings so we can increase production while still maintaining good quality in metal forming and similar manufacturing processes [19-21]. Therefore, the goal of this work is to find the best end-milling settings for EN24 steel. A Taguchi DOE is used to study how spindle speed, feed rate, and depth of cut affect surface roughness (*Ra*) and material removal rate (MRR). The results are analysed using S/N ratio and ANOVA, and the final optimal setting is verified using confirmation tests to give a practical recommendation for machining.

2. Method and material properties

2.1. Work piece materials

This study uses an EN24 specimen measuring $50\ mm \times 20\ mm$, as the main objective is to identify an appropriate set of machining parameters for high-speed machining (HSM) of the material. Table 1 and Table 2 summarize the material characteristics of EN24 steel used in this study. EN24 is a Ni-Cr-Mo medium-carbon alloy steel $(\mathrm{C} \approx 0.43\%)$ in which Ni $(\sim 2.0\%)$ improves toughness and fatigue resistance, Cr $(\sim 1.2\%)$ increases hardenability and wear resistance, and Mo $(\sim 0.25\%)$ supports strength retention; low P and S ($\sim 0.05\%$ each) help maintain consistent mechanical behavior. ASTM values correspond to Grade 4340 (AISI 4340) chemistry range, often used as an equivalent reference for EN24. Mechanically, EN24 shows high stiffness $(E \approx 210\ GPa)$, high strength $(YS\ 680-850\ MPa, UTS\ 850-1000\ MPa)$, moderate ductility ($13-17\%$ elongation), and hardness of $28-32\ HRC$ with fatigue strength around $370\ MPa$, making it suitable for loadbearing components and a challenging material for milling where cutting forces, tool wear, and surface finish are sensitive to parameter selection.

Table 1. Chemical composition of EN24 steel in $wt\%$.

Materials	Chemical composition in $wt\%$							
	C	Si	Mn	P	S	Cr	Mo	Ni
EN24	*0.43*	*0.4*	*0.9*	*0.05*	*0.05*	*1.2*	*0.25*	*2.0*
ASTM A29 Grade 4340	$0.38-0.43$	$0.15-0.35$	$0.60-0.80$	≤ 0.035	≤ 0.040	$0.70-0.90$	$0.20-0.30$	$1.65-2.00$

Table 2. Mechanical properties of EN24 steel.

Fatigue strength	Elastic Modulus	Yield strength	Ultimate tensile strength	Elongation	Hardness
MPa	*MPa*	*MPa*	*MPa*	%	*HRC*
370	*210*	$680-850$	$850-1000$	$13-17$	$28-32$

2.2. Cutting tool

EN24 is a medium-carbon Ni-Cr-Mo alloy steel widely used for highly stressed components such as shafts, gears, punches and dies because of its high tensile strength, toughness and wear resistance [22]. In the quenched-and-tempered *EN24T* condition, its machinability is only about $35-40$ % of that of mild steel *070M20* [23], so careful selection of cutting tool material and cutting parameters is essential to control surface quality and tool wear.

Several studies have reported successful machining of *EN24* using carbide tools. Das *et al.* performed high-speed dry turning of heat-treated *EN24* with uncoated tungsten carbide inserts and optimised cutting speed, feed and depth of cut using a Taguchi-grey relational approach [24]. Bharat *et al.* compared the turning behaviour of *EN24* and *EN36C* steels using carbide inserts and showed that *EN24* exhibits comparatively favourable machinability when tool wear and von Misses stress are considered [25].

In line with these findings, *EN24* in the present work was machined using a solid, uncoated $WC-Co$ carbide end mill of *12 mm* diameter with *4* flutes; the tool was selected from the manufacturer's standard solid-carbide end-mill series, having a flute length of *20 mm* and an overall length of *75 mm* [26]. A fresh tool was used for each experimental run so that variations in surface roughness and cutting forces could be attributed mainly to changes in cutting conditions rather than progressive tool wear.

2.3. Selection of parameter

During machining, surface quality is influenced by multiple interacting factors. Therefore, the key end-milling parameters must be selected according to the work piece material. In this study, the choice of process parameters was guided by findings from the literature. Figure 1 presents the main factors affecting surface finish in end milling. The parameters considered are A: cutting speed, B: feed rate, and C: depth of cut, as shown in Fig.2.

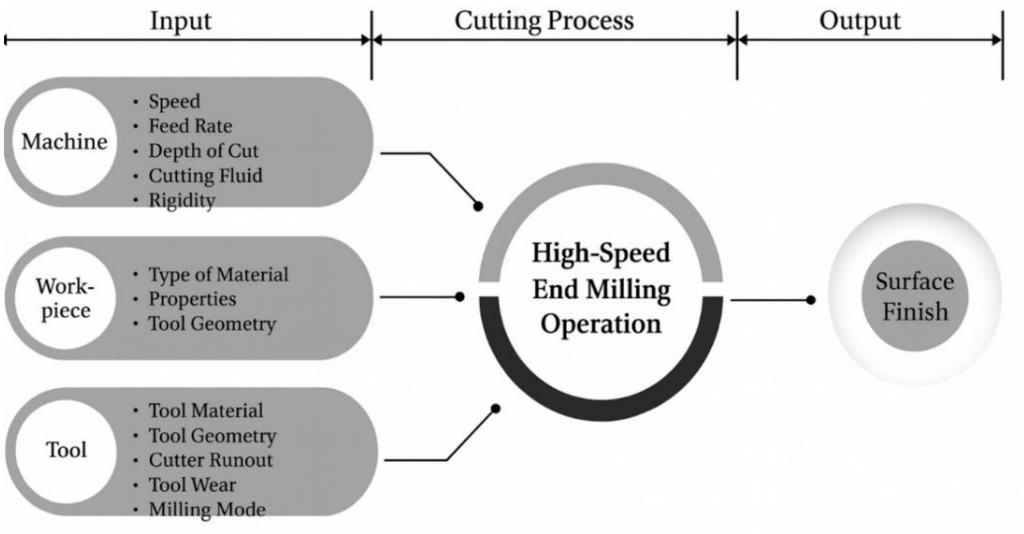

Fig.1. Surface finish influencing factors of milling process in high-speed mode.

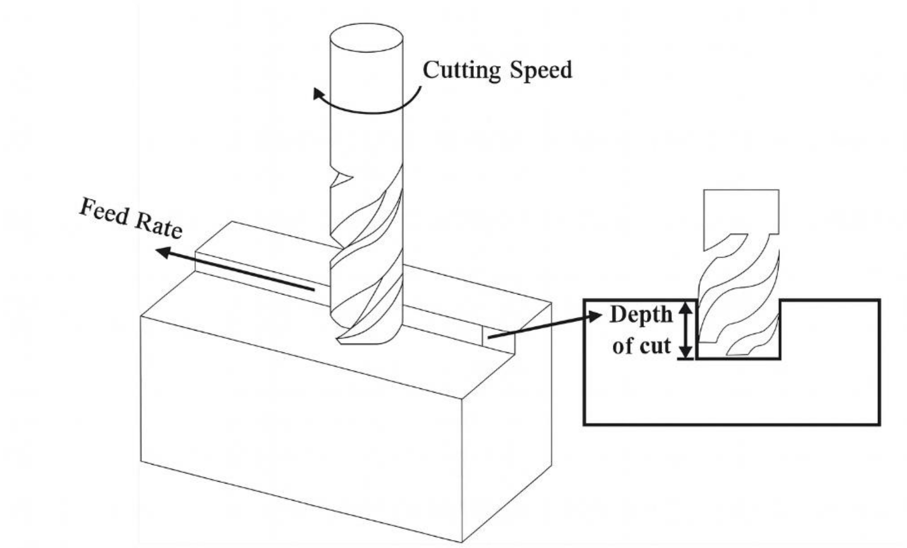

Fig.2. Selecting cutting parameters in high-speed milling process.

2.4. Cutting conditions

The machining experiments were carried out under dry conditions by varying three primary cutting parameters: spindle speed, feed rate and depth of cut. A Taguchi L27 orthogonal array was employed, considering spindle speed at three levels (220 , 340 and $600\ rpm$), feed rate at 88 , 102 and $118\ mm/min$, and depth of cut at 0.1 , 0.3 and $0.5\ mm$. For each trial combination, material removal rate (MRR) and surface roughness (*Ra*) were measured and the average of three replications was used for the analysis. The levels of the factors were selected based on tool-work piece capability and machine limitations so as to cover a practical industrial window while avoiding excessive tool loading. The experimental results were then analyzed using the "larger-the-better" criterion for MRR and the "smaller-the-better" criterion for *Ra* to identify suitable cutting conditions. The cutting conditions ranges in Tab.3 were selected based on the tool-work piece capability and machine limitations to represent a practical industrial window

Table 3. Cutting parameters and levels for milling of *EN24* steel.

Factor	Symbol	Unit	Level 1	Level 2	Level 3
Spindle speed	*N*	*rpm*	*220*	*340*	*600*
Feed Rate	*f*	*mm / min*	*88*	*102*	*118*
Depth of Cut	*ap*	*mm*	*0.10*	*0.30*	*0.50*

The experiments were conducted as per the cutting parameter combinations listed in Tab.3 using the Taguchi L27 orthogonal array. For each trial, surface roughness were measured, and the corresponding material removal rate was calculated. The obtained data were then analysed to study the influence of spindle speed, feed rate and depth of cut on surface integrity.

3. Result and discussion

3.1. Experimental results and Taguchi optimization for *Ra*

The experimental layout was developed using the Taguchi L27 orthogonal array to systematically study the effects of spindle speed, feed rate, and depth of cut at three levels. The complete design matrix and the measured surface roughness (*Ra*) for each experiment are provided in Tab.4.

For every experimental run, *Ra* was measured and the corresponding signal-to-noise (S/N) ratio was calculated using the *smaller-the-better* criterion; these S/N ratios for *Ra* are listed in Tab.5 (S/N ratios for *Ra*).

The *Ra* values obtained across the *27* trials show a wide variation, indicating a strong dependence of surface finish on the selected cutting parameters. In general, lower *Ra* values were associated with higher spindle speeds and appropriate combinations of feed and depth of cut, whereas intermediate speeds tended to give comparatively higher *Ra*. This trend is reflected both in the raw *Ra* data in Tab.4 and in the corresponding S/N ratios in Tab.5, where high-speed conditions yield larger (better) S/N values for *Ra*.

To quantify the relative influence of each factor, a response analysis of S/N ratios and mean *Ra* values was carried out. The response table of S/N ratios and mean values is given in Tab.6 (Response table of S/N ratios and mean *Ra*). From this table, spindle speed clearly emerges as the most influential parameter on *Ra*, showing the highest delta in both S/N ratio and mean response, followed by depth of cut, while feed rate has the least effect within the tested range. The optimal combination for minimum surface roughness, obtained from the S/N response table, corresponds to high spindle speed with moderate feed and suitable depth of cut. Confirmation experiments performed at this optimal setting yielded a significantly reduced *Ra* compared with the overall mean, confirming the effectiveness of the Taguchi approach in optimising surface finish.

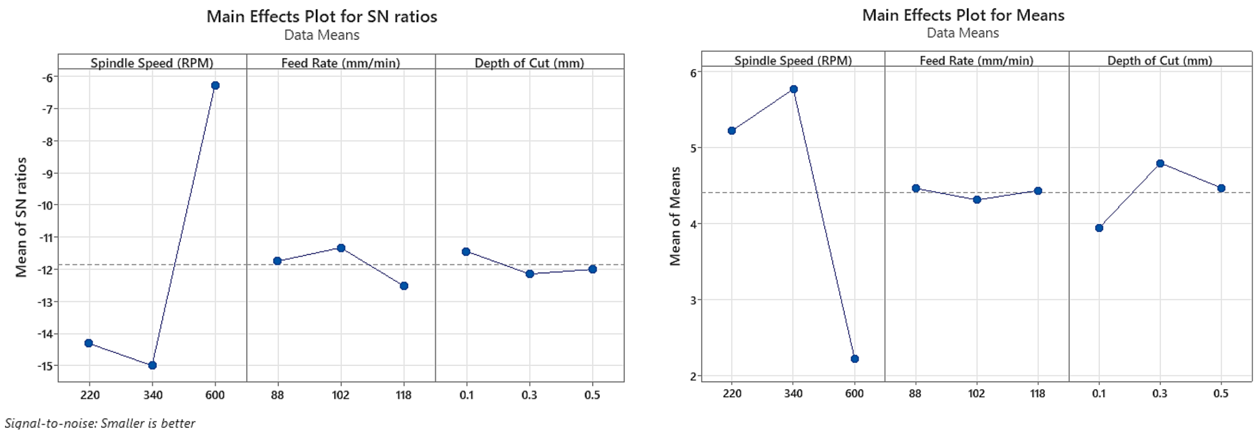

Fig.3. Effect of control factors on *Ra*.

The main-effects plots for means and S / N ratios as shown in Fig.3 clearly show that spindle speed is the dominant factor governing surface roughness during milling of EN24. As spindle speed increases from 220 to $600\ rpm$, the mean Ra drops sharply from about $5.2 - 5.8\ \mu m$ to nearly $2.2\ \mu m$, and the corresponding S / N ratio improves markedly, indicating a much more stable and finer surface finish at the highest speed level. In contrast, feed rate produces only a slight variation in *Ra* within the investigated range, and its S / N curve remains almost flat around the overall mean, confirming that feed is the least influential parameter for *Ra* in this study.

Table 4. Experimental design and measured average surface roughness (*Ra*).

Test run	Spindle speed $[RPM]$	Feed rate $[mm / min]$	Depth of cut $[mm]$	Avg MRR $[mm^3 / min]$	Avg Ra $[\mu m]$
1	600	88	0.1	176	1.461
2	600	102	0.3	612	1.197
3	600	118	0.5	1180	3.791
4	600	88	0.3	528	2.301
5	600	102	0.5	1020	1.361
6	600	118	0.1	236	3.15
7	600	88	0.5	880	1.766
8	600	102	0.1	204	3.124
9	600	118	0.3	708	1.859
10	340	88	0.1	176	4.309
11	340	102	0.3	612	8.076
12	340	118	0.5	1180	5.708
13	340	88	0.3	528	7.528
14	340	102	0.5	1020	4.535
15	340	118	0.1	236	4.48
16	340	88	0.5	880	7.259
17	340	102	0.1	204	4.839
18	340	118	0.3	708	5.217
19	220	88	0.1	176	4.461
20	220	102	0.3	612	6.373
21	220	118	0.5	1180	5.605
22	220	88	0.3	528	5.761
23	220	102	0.5	1020	4.878
24	220	118	0.1	236	5.251
25	220	88	0.5	880	5.351
26	220	102	0.1	204	4.45
27	220	118	0.3	708	4.887

Table 5. Signal-to-noise (S/N) ratios for surface roughness (Ra) (smaller-the-better).

Test Run	Spindle speed $[RPM]$	Feed rate $[mm/min]$	Depth of cut $[mm]$	Avg Ra $[\mu m]$	S/N ratio for Ra
1	*600*	*88*	*0.1*	*176*	*–3.2930*
2	*600*	*102*	*0.3*	*612*	*–1.5619*
3	*600*	*118*	*0.5*	*1180*	*–11.5751*
4	*600*	*88*	*0.3*	*528*	*–7.2383*
5	*600*	*102*	*0.5*	*1020*	*–2.6772*
6	*600*	*118*	*0.1*	*236*	*–9.9662*
7	*600*	*88*	*0.5*	*880*	*–4.9398*
8	*600*	*102*	*0.1*	*204*	*–9.8942*
9	*600*	*118*	*0.3*	*708*	*–5.3856*
10	*340*	*88*	*0.1*	*176*	*–12.6875*
11	*340*	*102*	*0.3*	*612*	*–18.1439*
12	*340*	*118*	*0.5*	*1180*	*–15.1297*
13	*340*	*88*	*0.3*	*528*	*–17.5336*
14	*340*	*102*	*0.5*	*1020*	*–13.1315*
15	*340*	*118*	*0.1*	*236*	*–13.0256*
16	*340*	*88*	*0.5*	*880*	*–17.2175*
17	*340*	*102*	*0.1*	*204*	*–13.6951*
18	*340*	*118*	*0.3*	*708*	*–14.3484*
19	*220*	*88*	*0.1*	*176*	*–12.9886*
20	*220*	*102*	*0.3*	*612*	*–16.0869*
21	*220*	*118*	*0.5*	*1180*	*–14.9715*
22	*220*	*88*	*0.3*	*528*	*–15.2100*
23	*220*	*102*	*0.5*	*1020*	*–13.7648*
24	*220*	*118*	*0.1*	*236*	*–14.4048*
25	*220*	*88*	*0.5*	*880*	*–14.5687*
26	*220*	*102*	*0.1*	*204*	*–12.9672*
27	*220*	*118*	*0.3*	*708*	*–13.7808*

Table 6. Response table of S/N ratios and mean Ra for each factor and level.

Level	S/N (Spindle speed)	S/N (Feed rate)	S/N (Depth of cut)	Mean (Spindle speed)	Mean (Feed rate)	Mean (Depth of cut)
1	*–14.305*	*–11.742*	*–11.436*	*5.224*	*4.466*	*3.947*
2	*–14.990*	*–11.325*	*–12.143*	*5.772*	*4.315*	*4.800*
3	*–6.281*	*–12.510*	*–11.997*	*2.223*	*4.439*	*4.473*
Delta	*8.709*	*1.185*	*0.707*	*3.549*	*0.152*	*0.853*
Rank	*1*	*2*	*3*	*1*	*3*	*2*

3.3. Contour plots and validation of optimal conditions

Contour plots as in Fig.4 are used to visualise the combined effect of pairs of cutting parameters on *Ra*. The interaction between spindle speed and depth of cut, and between feed rate and depth of cut, is examined over the experimental domain. Low-*Ra* regions are identified on the maps, thereby highlighting favourable operating zones for achieving fine surface finish.

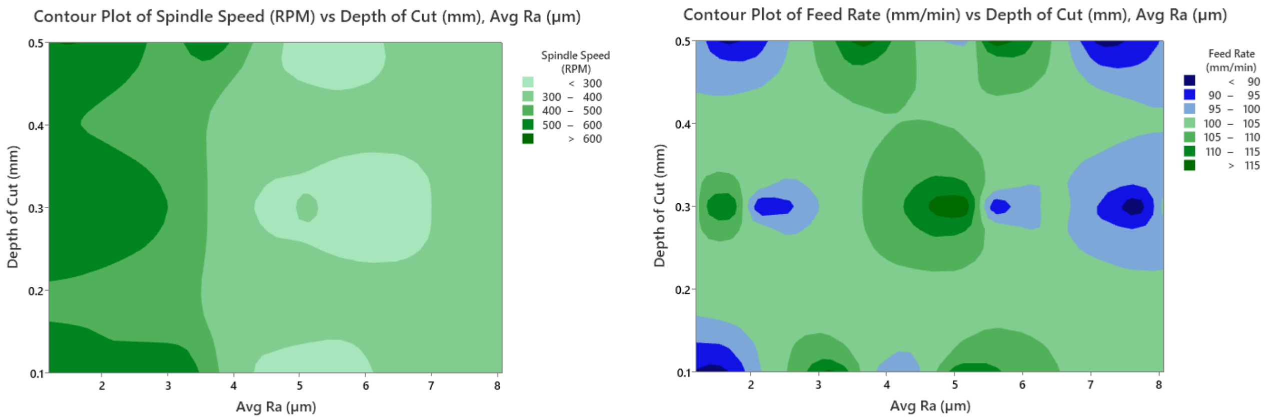

Fig.4. Contour plot of spindle speed and feed rate.

For depth of cut, the lowest *Ra* and the best S/N ratio are obtained at $0.1\ mm$, while $0.3\ mm$ gives the poorest surface finish, suggesting that intermediate depths promote higher cutting forces and tool-workpiece interaction, leading to increased roughness. Taken together, the plots indicate that the optimal setting for minimum *Ra* is the combination of high spindle speed $(600\ rpm)$, moderate feed $(102\ mm/min)$ and low depth of cut $(0.1\ mm)$. This confirms the Taguchi response table results and highlights that operating at higher cutting speeds with a relatively small depth of cut is essential for achieving superior surface quality when machining EN24 steel with carbide tools.

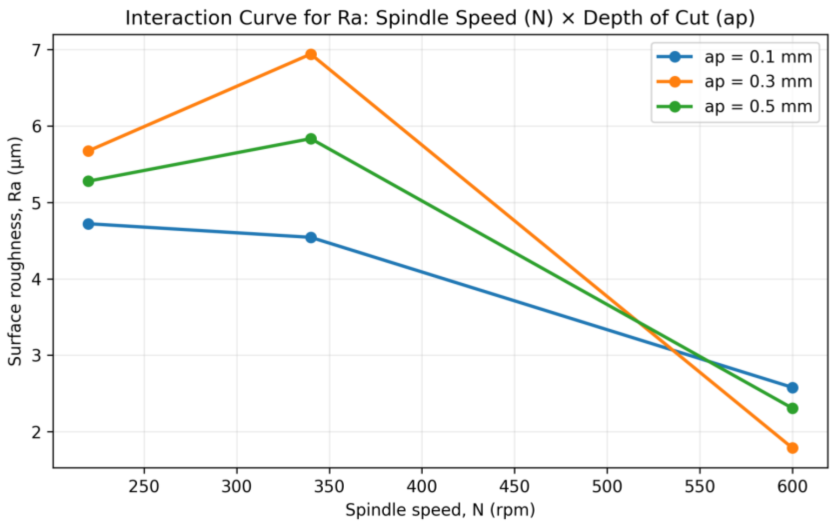

Fig.5. Interaction curve for effect of spindle speed (N) and depth of cut (ap) on surface roughness (Ra).

Fig.5. presents the interaction curve between spindle speed (N) and depth of cut (ap) for surface roughness (Ra). The curves are non-parallel, indicating that the influence of *ap* on *Ra* depends on the spindle-speed level. Overall, increasing spindle speed improves surface finish, consistent with the main-effect trend reported in this study. At the intermediate speed level $(340\ rpm)$, *Ra* increases sharply – particularly around $ap = 0.3\ mm$ – suggesting that this engagement condition promotes higher cutting forces and stronger tool – work interaction, which deteriorates the generated surface. In contrast, at the highest speed $(600\ rpm)$ the *Ra* values remain comparatively lower across ap levels, showing a more stable finishing window. These interaction trends support the selection of a high-speed, low-depth combination for surface-integrity-focused machining of EN24 within the investigated parameter range.

3.4. Analysis of variance (ANOVA) for *Ra*

To quantify the statistical significance of each cutting parameter on surface roughness, a one-way ANOVA was performed on the average *Ra* values obtained from the Taguchi L27 experiments. The factors considered were spindle speed (A), feed rate (B) and depth of cut (C), each at three levels. Interactions were assumed to be small and were pooled into the error term, which is a common practice in Taguchi analysis. The overall mean surface roughness for all 27 trials was $4.41\ \mu m$. The ANOVA results for *Ra* are presented in Tab.7. All three cutting parameters exhibit very large *F*-ratios ($FA = 43.19$, $FB = 95.06$ and $FC = 65.83$), each well above the critical value $F_{0.05,\ (2,20)} = 3.49$ The corresponding p-values ($p < 0.001$ for all factors) confirm that spindle speed, feed rate and depth of cut all have statistically significant effects on surface roughness at the 95% confidence level. Among these, feed rate is the most influential factor, followed by depth of cut and spindle speed.

Table 7. Analysis of variance (ANOVA) for surface roughness *Ra*.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Spindle speed $[rpm]$	2	229.74	114.87	43.19	0.000	19.30
Feed rate $[mm/min]$	2	557.2	252.86	95.06	0.000	46.81
Depth of cut $[mm]$	2	350.28	175.14	65.83	0.000	29.42
Error	20	53.23	2.66			4.47
Total	26	1190.45				100
$S = 1.63 \quad R-sq = 95.53\% \quad R-sq(adj) = 94.19\%$						

The percentage contribution column indicates that feed rate accounts for approximately 46.8% of the total variation in *Ra*, depth of cut for about 29.4% and spindle speed for about 19.3%, while the remaining 4.5% is attributed to experimental error and unmodelled interactions. These results corroborate the main-effects a plot, confirming that feed rate is the dominant control parameter for improving surface finish in milling EN24 steel, with spindle speed and depth of cut also exerting strong but comparatively smaller influences within the present parameter window.

The regression model shows a good fit to the experimental data, with a standard error of regression $S = 1.63\,\mu m$ indicating relatively small residual scatter around the fitted line. The high coefficient of determination $(R^2 = 95.53\%)$ means that the cutting parameters explain almost all of the variation in surface roughness, while the adjusted value $(R^2(adj) = 94.19\%)$ confirms that this explanatory power remains strong even after accounting for the number of terms in the model.

3.5. Confirmation of experiment

To validate the optimal cutting conditions identified by the Taguchi analysis, a confirmation experiment was carried out at the parameter combination Spindle speed $= 600\ rpm$, Feed rate $= 102\ mm/min$ and Depth of cut $= 0.1\ mm$. The corresponding S/N ratio was predicted using the standard additive model based on factor-level means, with the grand mean S/N ratio $S/N = -11.43$ and the individual level effects for spindle speed, feed rate and depth of cut. Substituting the respective level means into the prediction equation yielded a theoretical S/N ratio of $S/N = -10.55$ for the optimal setting. The confirmation test conducted at this combination provides an experimental check on the robustness of the Taguchi model, allowing the measured S/N ratio from the confirmation run to be compared directly with the predicted value. The close agreement between the predicted and confirmation results demonstrates that the selected parameter combination is indeed effective in improving surface finish and that the developed Taguchi-ANOVA model offers a reliable representation of the surface roughness behaviour in milling EN24 steel within the investigated design space.

Table 8. Comparison of *Ra*.

Condition	Spindle Speed $[rpm]$	Feed Rate $[mm/min]$	Depth of Cut $[mm]$	$Ra\ [\mu m]$	S/N ratio for *Ra*	Reduction in *Ra* vs. reference [%]
Reference Overall mean of L27 trials	–	–	–	*4.410*	*−11.43*	*00*
Optimal Combination (Taguchi prediction)	*600*	*557.2*	*252.86*	*3.369*	*−10.55*	*23.61*
Optimal Combination (Confirmation experiment)	*600*	*350.28*	*175.14*	*3.124*	*−9.91*	*29.16*

Error percentage

$$\text{Error } \% = |\text{ Actual } S/N - \text{Predicted } S/N.| \,/\, |\text{ Actual } S/N.| \times 100$$

$$|\text{ Actual } S/N - \text{Predicted } S/N.| = |-9.91 - (-10.55).| = 0.64$$

$$|\text{ Actual } S/N.| = -9.91$$

$$\text{Error } \% = \left(\frac{0.64}{9.91}\right) \times 100 \approx 6.46\ \%$$

The difference between the predicted and experimental S/N ratios is only about 6.46%, indicating good agreement between the Taguchi model and the confirmation test. This small error confirms that the developed predictive model is reliable and that the selected optimal cutting parameters are robust for achieving improved surface finish.

4. Conclusion

This study investigated the effects of three machining factors on high-speed end milling of EN24 under dry conditions, namely cutting speed, feed rate and depth of cut (DOC). Over the cutting speed range corresponding to spindle speeds of $220-600\ rpm$, with feeds from $88-118\,mm/min$ and DOC from $0.1-0.5\ mm$, the optimum cutting parameters and their relative importance were established so that robust operating conditions can be selected without lubricant.

1. The Taguchi L27 orthogonal array proved effective for analysing and optimising both material removal rate (MRR) and surface roughness (*Ra*) in milling of EN24 steel. It provides a systematic and economical way to study multiple parameters simultaneously.
2. ANOVA for MRR showed that depth of cut is the most dominant factor, while spindle speed and feed rate have comparatively smaller effects. For *Ra*, feed rate was the most influential factor, followed by depth of cut and spindle speed.
3. The developed regression models for MRR and *Ra* showed high coefficients of determination $\left(R^2 \approx 95\%\right)$. This indicates that the selected cutting parameters explain most of the variation and can be reliably used for prediction.
4. The optimal setting for maximum MRR was $600\ rpm$ spindle speed, $118\ mm/min$ feed, and $0.5\ mm$ depth of cut. For minimum *Ra*, the best combination was $600\ rpm$ spindle speed, $102\ mm/min$ feed, and $0.1\ mm$ depth of cut, which was validated by confirmation tests.
5. Overall, the study confirms that Taguchi-based optimisation is a practical tool to enhance productivity while maintaining acceptable surface finish in milling of EN24 steel. The approach can be extended in future work to include tool wear, energy consumption, and different tool/coating and cooling conditions.
6. The best surface finish was achieved at high speed with moderate feed and low depth of cut, while maximum MRR occurred at high feed and high depth of cut. This agrees with earlier studies that report a clear MRR-*Ra* trade-off, where increasing feed/engagement boosts productivity but can worsen roughness.

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Nomenclature

$ANOVA$	– analysis of variance
a	– depth of cut $[mm]$
f	– feed rate $[mm/min]$
MRR	– material removal rate $[mm^3/min]$
N	– spindle speed $[rpm]$
Ra	– surface roughness $[\mu m]$
$\frac{S}{N}$	– signal-to-noise ratio

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