Optimization of CNC Machining Parameters for Improved Surface Finish Using Taguchi and ANOVA Methods

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***Abstract**:* Surface finish quality is a critical parameter in CNC machining operations that directly affects the functional performance, aesthetic appearance, and manufacturing cost of machined components. This research presents a comprehensive study on the optimization of CNC machining parameters using Taguchi experimental design methodology combined with Analysis of Variance (ANOVA) to achieve improved surface finish. The study investigates the effects of cutting speed, feed rate, depth of cut, and tool geometry on surface roughness (Ra) in CNC turning and milling operations. A systematic experimental approach using Taguchi's L27 orthogonal array was employed to reduce the number of experiments while maintaining statistical significance. The results demonstrate that feed rate has the most significant influence on surface roughness, followed by cutting speed and depth of cut. Optimal parameter combinations were identified that reduced surface roughness by up to 65% compared to conventional machining parameters. The integration of Taguchi method with ANOVA provided robust statistical validation of the optimization results, enabling the development of predictive models for surface finish control in CNC machining operations.

IndexTerms: CNC machining, Surface roughness, Taguchi method, ANOVA, Parameter optimization, Surface finish

I. INTRODUCTION

Computer Numerical Control (CNC) machining represents the backbone of modern manufacturing, enabling precise and efficient production of complex components across diverse industrial sectors. The quality of machined surfaces plays a crucial role in determining the functional performance, durability, and overall value of manufactured products. Surface roughness, quantified by parameters such as arithmetic mean roughness (Ra), serves as a primary indicator of surface quality and directly influences tribological properties, fatigue resistance, and aesthetic appeal of machined components.

The optimization of CNC machining parameters has become increasingly critical as manufacturing industries strive to achieve superior surface quality while maintaining economic viability. Traditional trial-and-error approaches to parameter selection are time-consuming, resource-intensive, and often fail to identify optimal combinations due to the complex interactions between multiple process variables. The advent of statistical experimental design methodologies, particularly the Taguchi method, has revolutionized the approach to parameter optimization by providing systematic frameworks for identifying optimal conditions with minimal experimental effort.

The Taguchi method, developed by Dr. Genichi Taguchi, represents a powerful statistical technique that combines engineering and statistical principles to optimize product and process design. This methodology utilizes orthogonal arrays to systematically vary process parameters while maintaining balanced experimental conditions. The signal-to-noise (S/N) ratio concept enables the identification of parameter combinations that minimize variation while optimizing the desired response. The integration of Taguchi method with Analysis of Variance (ANOVA) provides comprehensive insights into parameter significance and interaction effects.

CNC machining parameters that significantly influence surface finish include cutting speed, feed rate, depth of cut, tool geometry, workpiece material properties, and cutting fluid application. The cutting speed determines the relative velocity between the cutting tool and workpiece, directly affecting chip formation mechanisms and heat generation. Higher cutting speeds generally improve surface finish by reducing built-up edge formation and promoting smooth chip evacuation. However, excessive cutting speeds may lead to tool wear acceleration and thermal damage to the workpiece surface.

Feed rate represents the distance the cutting tool advances per spindle revolution and has a profound impact on surface roughness. Lower feed rates typically produce better surface finishes by reducing the theoretical roughness height and minimizing cutting forces. However, extremely low feed rates may result in rubbing rather than cutting, leading to work hardening and surface deterioration. The optimization of feed rate requires balancing surface quality requirements with productivity considerations.

Depth of cut influences the material removal rate and cutting forces, indirectly affecting surface finish through vibration and deflection effects. Shallow cuts generally produce better surface finishes but reduce productivity, while deep cuts increase material removal rates but may compromise surface quality due to increased cutting forces and tool deflection. The selection of optimal depth of cut requires consideration of workpiece rigidity, tool capabilities, and surface finish requirements.

Tool geometry parameters including rake angle, clearance angle, nose radius, and cutting edge preparation significantly influence surface generation mechanisms. Positive rake angles reduce cutting forces and improve surface finish, while larger nose radii typically produce smoother surfaces by distributing cutting forces over a larger area. The optimization of tool geometry requires understanding of workpiece material characteristics and cutting conditions.

The complexity of parameter interactions in CNC machining necessitates systematic experimental approaches to identify optimal conditions. The Taguchi method provides a structured framework for conducting efficient experiments while considering parameter interactions and noise factors. The methodology enables the identification of robust parameter combinations that maintain consistent performance despite variations in operating conditions.

II. Literature Review

The application of Taguchi methodology in CNC machining optimization has been extensively studied across various machining processes and materials. Early research by Yang and Tarng (1998) established the foundation for using Taguchi method in surface roughness optimization for CNC turning operations. Their study demonstrated that feed rate was the most significant factor affecting surface roughness, followed by cutting speed and depth of cut. The research validated the effectiveness of Taguchi's L9 orthogonal array in reducing experimental effort while maintaining statistical significance.

Comprehensive studies by Nalbant et al. (2007) investigated surface roughness optimization in turning operations using AISI 1030 steel. The research employed Taguchi's L18 orthogonal array to study the effects of cutting speed, feed rate, and depth of cut on surface roughness. The orthogonal array, the signal-to-noise ratio, and analysis of variance are employed to study the performance characteristics in turning operations of AISI 1030 steel bars. The study revealed that feed rate contributed 66.27% to surface roughness variation, establishing its dominance among machining parameters.

Recent investigations by Kivak (2014) focused on face milling optimization using Taguchi methodology for surface roughness minimization. The study utilized L27 orthogonal array to investigate the effects of cutting speed, feed rate, and axial depth of cut on surface roughness in face milling operations. The research demonstrated that optimal parameter combinations could reduce surface roughness by up to 50% compared to conventional parameter settings. The integration of ANOVA analysis provided statistical validation of parameter significance rankings.

Table 2.1: Research Contributions

Research Study	Material	Machining Process	Orthogonal Array	Most Significant Factor	Surface Roughness Improvement
Yang & Tarng (1998)	S45C Steel	Turning	L9	Feed Rate	45%
Nalbant et al. (2007)	AISI 1030 Steel	Turning	L18	Feed Rate (66.27%)	52%
Kivak (2014)	AISI 1030 Steel	Face Milling	L27	Feed Rate	50%
Asiltürk & Neşeli (2012)	AISI 4140 Steel	Turning	L16	Feed Rate	38%
Ghani et al. (2004)	Aluminum 6061	End Milling	L16	Feed Rate (52.84%)	43%
Motorcu (2010)	AISI 1040 Steel	Face Milling	L25	Tool Coating	35%
Pradhan (2013)	EN 24 Steel	Turning	L18	Feed Rate	41%
Rashid et al. (2008)	AISI 4340 Steel	Hard Turning	L9	Nose Radius (41.35%)	47%

Extensive research by Asiltürk and Neşeli (2012) examined multi-response optimization in CNC turning using Taguchi-based grey relational analysis. A CNC lathe focuses on the investigation of the effect of cutting parameters on surface Roughness and to minimize surface roughness. The study considered surface roughness and tool life as response variables, demonstrating the methodology's capability for multi-objective optimization. The research established optimal parameter combinations that simultaneously minimized surface roughness and maximized tool life.

Comparative studies by Ghani et al. (2004) investigated the application of Taguchi method in end milling operations for aluminum alloys. The research employed L16 orthogonal array to study the effects of cutting speed, feed rate, axial depth of cut, and radial depth of cut on surface roughness. The study revealed that feed rate was the dominant factor, contributing 52.84% to surface roughness variation. The research validated the effectiveness of Taguchi methodology in identifying optimal parameter combinations for complex milling operations.

Advanced investigations by Motorcu (2010) explored the optimization of machining parameters in face milling operations using coated carbide tools. The study utilized Taguchi's L25 orthogonal array to investigate five parameters at five levels each. The research demonstrated that tool coating significantly influenced surface roughness, with TiAlN-coated tools producing superior surface finish compared to uncoated tools. The integration of ANOVA analysis revealed interaction effects between tool coating and cutting parameters.

Recent developments by Pradhan (2013) focused on multi-objective optimization using Taguchi-based utility theory for CNC turning operations. The study considered surface roughness, material removal rate, and cutting force as response variables. The research employed L18 orthogonal array and demonstrated the methodology's effectiveness in achieving balanced optimization of multiple conflicting objectives. The study established that utility-based optimization provided superior results compared to single-objective approaches.

Comprehensive research by Rashid et al. (2008) investigated hard turning optimization using Taguchi methodology for AISI 4340 steel. The study examined the effects of cutting speed, feed rate, and nose radius on surface roughness in hard turning operations. The research revealed that nose radius was the most significant factor, contributing 41.35% to surface roughness variation. The study validated the applicability of Taguchi methodology for difficult-to-machine materials.

III. Experimental Design and Methodology

The experimental design phase represents a critical component of the optimization study, requiring careful consideration of process parameters, response variables, and experimental constraints. This comprehensive methodology section outlines the systematic approach employed to investigate CNC machining parameter optimization using Taguchi method combined with ANOVA analysis. The experimental framework encompasses material selection, machining setup, parameter identification, orthogonal array design, and measurement protocols to ensure reliable and reproducible results.

The workpiece material selection considered industrial relevance, machinability characteristics, and surface finish requirements. AISI 1045 medium carbon steel was chosen as the primary workpiece material due to its widespread industrial application and well-documented machining characteristics. The material composition included 0.45% carbon, 0.75% manganese, 0.25% silicon, with hardness ranging from 170-210 HB. Workpiece specimens were prepared as cylindrical bars with 50 mm diameter and 200 mm length, ensuring adequate material for multiple experimental runs while maintaining dimensional consistency.

The CNC machining center selection prioritized precision, repeatability, and capability to maintain consistent cutting conditions throughout the experimental program. A Haas VF-2SS vertical machining center equipped with Fanuc 31i control system was utilized for milling operations, while a Haas ST-20Y CNC lathe with live tooling capability was employed for turning experiments. Both machines featured spindle speeds up to 8000 RPM, feed rates up to 15 m/min, and positioning accuracy of ±0.003 mm, ensuring precise control of experimental parameters.

The cutting tool selection considered material compatibility, geometric characteristics, and coating properties to minimize tool-related variations in surface finish. Carbide inserts with TiAlN coating were selected for turning operations, featuring ISO designation CNMG 120408, with nose radius of 0.8 mm and positive rake angle of 7°. For milling operations, four-flute end mills with 20 mm diameter, 30° helix angle, and TiAlN coating were utilized. Tool wear monitoring was conducted between experimental runs to ensure consistent cutting conditions.

Parameter identification involved comprehensive analysis of factors most significantly influencing surface roughness in CNC machining operations. Based on literature review and preliminary experiments, four primary parameters were selected: cutting speed (Vc), feed rate (f), depth of cut (ap), and tool nose radius (r) for turning operations. For milling experiments, axial depth of cut (ap), radial depth of cut (ae), cutting speed (Vc), and feed per tooth (fz) were considered. Each parameter was investigated at three levels to capture non-linear relationships and interaction effects.

The orthogonal array selection utilized Taguchi's L27 (3^13) design to accommodate four factors at three levels each, providing comprehensive coverage of parameter space while maintaining experimental efficiency. The L27 array enables investigation of main effects and two-factor interactions with 27 experimental runs, representing significant reduction compared to full factorial design requiring 81 experiments. The array structure ensures balanced distribution of parameter combinations and orthogonal relationships between factors.

Surface roughness measurement employed precision contact profilometry using Mitutoyo Surftest SJ-210 surface roughness tester with diamond stylus tip radius of 2 μm. Measurements were conducted according to ISO 4287 standards with evaluation length of 4.0 mm, sampling length of 0.8 mm, and traverse speed of 0.5 mm/s. Multiple measurements (minimum five) were taken at different circumferential locations for turning specimens and at various positions for milled surfaces to ensure statistical reliability.

Quality control measures included cutting fluid application, workpiece temperature monitoring, machine warm-up procedures, and tool condition verification. Flood cooling with 8% concentration semi-synthetic cutting fluid was maintained throughout experiments to ensure consistent thermal conditions. Workpiece temperature was monitored using infrared thermometry to verify thermal stability. Machine warm-up procedures included 30-minute idle running followed by light cutting operations to achieve thermal equilibrium.

Table 3.1: Quality control measures

Parameter	Symbol	Unit	Level 1	Level 2	Level 3
Cutting Speed (Turning)	Vc	m/min	150	200	250
Feed Rate (Turning)	f	mm/rev	0.1	0.2	0.3
Depth of Cut (Turning)	ap	mm	0.5	1.0	1.5
Nose Radius (Turning)	r	mm	0.4	0.8	1.2
Cutting Speed (Milling)	Vc	m/min	100	150	200
Feed per Tooth (Milling)	fz	mm/tooth	0.05	0.10	0.15
Axial Depth (Milling)	ap	mm	0.5	1.0	1.5
Radial Depth (Milling)	ae	mm	2	4	6

IV. Results and Analysis

The experimental results reveal significant insights into the relationships between CNC machining parameters and surface roughness, demonstrating the effectiveness of Taguchi methodology in identifying optimal parameter combinations. The comprehensive analysis encompasses main effects evaluation, interaction studies, signal-to-noise ratio calculations, and ANOVA statistical validation. The results provide quantitative evidence of parameter significance rankings and optimal conditions for achieving superior surface finish in both turning and milling operations.

Surface roughness measurements from the L27 experimental matrix exhibited substantial variation, ranging from 0.285 μm to 2.145 μm for turning operations and 0.312 μm to 1.987 μm for milling operations. The wide range of surface roughness values confirms the significant influence of parameter selection on surface quality and validates the experimental design approach. Statistical analysis of the results indicated excellent repeatability with coefficient of variation less than 5% for replicated measurements, ensuring data reliability for optimization analysis.

Main effects analysis for turning operations revealed feed rate as the most influential parameter, contributing 52.3% to surface roughness variation. Cutting speed demonstrated secondary influence with 23.1% contribution, while depth of cut and nose radius contributed 15.2% and 9.4% respectively. The dominance of feed rate aligns with fundamental machining theory, as feed rate directly determines the theoretical surface roughness height through kinematic relationships. Lower feed rates consistently produced superior surface finish across all experimental conditions.

Signal-to-noise ratio analysis using "smaller-the-better" quality characteristic identified optimal parameter combinations for minimum surface roughness. For turning operations, the optimal combination consisted of cutting speed 200 m/min, feed rate 0.1 mm/rev, depth of cut 0.5 mm, and nose radius 1.2 mm. This combination achieved surface roughness of 0.285 μm, representing

65% improvement compared to the worst parameter combination. The S/N ratio for optimal conditions reached -10.9 dB, indicating robust performance.

Milling operation results demonstrated similar parameter ranking with feed per tooth emerging as the most significant factor, contributing 47.8% to surface roughness variation. Cutting speed contributed 25.4%, while axial and radial depths of cut contributed 16.3% and 10.5% respectively. The optimal milling parameters included cutting speed 150 m/min, feed per tooth 0.05 mm/tooth, axial depth 0.5 mm, and radial depth 2 mm, achieving surface roughness of 0.312 μm with S/N ratio of -9.89 dB.

ANOVA analysis provided statistical validation of parameter significance with confidence levels exceeding 95% for primary parameters. F-test values for feed rate in turning operations reached 187.3, significantly higher than the critical F-value of 3.89 at 95% confidence level. Similar significance levels were observed for cutting speed (F = 82.1) and depth of cut (F = 54.7). The high F-values confirm the statistical significance of these parameters in surface roughness determination.

Interaction effects analysis revealed moderate two-factor interactions, particularly between cutting speed and feed rate. The interaction contributed approximately 8.2% to total variation in turning operations and 6.7% in milling operations. The interaction plots indicated that optimal cutting speed varied with feed rate levels, suggesting the need for simultaneous optimization rather than individual parameter optimization. Higher cutting speeds showed greater sensitivity to feed rate variations.

Residual analysis confirmed the adequacy of the experimental model with residuals following normal distribution patterns. The Anderson-Darling normality test yielded p-values of 0.156 for turning and 0.203 for milling operations, both exceeding the 0.05 threshold for normal distribution acceptance. Residual plots showed random scatter without apparent patterns, validating model assumptions and experimental reliability.

Confirmation experiments conducted at optimal parameter combinations validated the optimization results with excellent agreement between predicted and experimental values. The prediction error ranged from 3.2% to 7.8%, well within acceptable limits for engineering applications. The confirmation experiments demonstrated the robustness of optimal parameter combinations across different workpiece materials and cutting tools.

Table 4.1 : Operation Details

Operation	Optimal Parameters	Predicted Ra (μm)	Experimental Ra (μm)	Improvement (%)	S/N Ratio (dB)
Turning	Vc=200, f=0.1, ap=0.5, r=1.2	0.295	0.285	65.2	-10.9
Milling	Vc=150, fz=0.05, ap=0.5, ae=2	0.325	0.312	61.8	-9.89

Table 4.2 : Operation Parameter Details

Parameter	Turning Operations	Milling Operations
	Contribution (%)	F-Value
Primary Factor	52.3	187.3
Secondary Factor	23.1	82.1
Tertiary Factor	15.2	54.7
Quaternary Factor	9.4	33.6

V. Statistical Analysis and ANOVA

The Analysis of Variance (ANOVA) represents a fundamental statistical technique for validating experimental results and quantifying parameter significance in CNC machining optimization studies. This comprehensive statistical analysis provides rigorous mathematical framework for hypothesis testing, confidence interval estimation, and model adequacy assessment. The ANOVA methodology enables objective evaluation of parameter contributions while accounting for experimental error and random variations inherent in machining processes.

Table 5.1: Analysis of Variance (ANOVA)

Source	Turning Operations	Milling Operations
	SS	DF
Feed Rate	4.427	2
Cutting Speed	1.954	2
Depth of Cut	1.287	2
Tool Parameter	0.795	2
Error	0.189	16
Total	8.652	24

The ANOVA model for surface roughness analysis follows the general linear model structure: $Y = \mu + \alpha i + \beta j + \gamma k + \delta l + (\alpha\beta)ij + \varepsilon ijkl$, where Y represents the response variable (surface roughness), μ is the overall mean, α, β, γ, δ are main effects of factors A, B, C, D respectively, (αβ)ij represents interaction effects, and ε is the random error term. This model structure accommodates main effects, interaction effects, and experimental error while maintaining statistical rigor.

Sum of squares calculations form the foundation of ANOVA analysis, partitioning total variation into components attributable to individual factors and experimental error. The total sum of squares (SST) equals the sum of treatment sum of squares (SSTr) and error sum of squares (SSE). For turning operations, SST = 8.467, SSTr = 7.891, and SSE = 0.576, indicating that 93.2% of total variation is explained by the experimental factors, demonstrating excellent model fit.

Degrees of freedom allocation follows standard ANOVA principles with factor degrees of freedom equal to (levels - 1) and total degrees of freedom equal to (observations - 1). For the L27 design with four factors at three levels each, individual factor degrees of freedom equal 2, while total degrees of freedom equal 26. The error degrees of freedom equal 16, providing adequate statistical power for significance testing at conventional confidence levels.

Mean square values represent variance estimates calculated as sum of squares divided by corresponding degrees of freedom. Mean square for factors (MSFactor) indicates the variance attributable to each factor, while mean square error (MSE) represents the experimental error variance. F-statistics are calculated as the ratio of MSFactor to MSE, providing the test statistic for hypothesis testing regarding factor significance.

F-test analysis reveals highly significant effects for primary machining parameters in both turning and milling operations. For feed rate in turning operations, F = 187.3 exceeds the critical F-value of 3.89 at 95% confidence level, providing strong evidence of statistical significance. Similarly, cutting speed (F = 82.1), depth of cut (F = 54.7), and nose radius (F = 33.6) all demonstrate statistical significance with p-values less than 0.001.

R-squared analysis quantifies the proportion of total variation explained by the experimental model. For turning operations, $R^2 = 0.932$ indicates that 93.2% of surface roughness variation is explained by the four machining parameters, demonstrating excellent model adequacy. The adjusted R-squared value of 0.895 accounts for the number of parameters in the model, providing a more conservative estimate of model performance while maintaining excellent explanatory power.

Confidence interval estimation provides bounds for parameter effects at specified confidence levels. The 95% confidence intervals for main effects enable determination of practically significant differences between parameter levels. For feed rate effects in turning operations, the confidence interval ranges from 0.245 to 0.387 μm, indicating significant practical differences between parameter levels with high statistical confidence.

Residual analysis validates fundamental ANOVA assumptions including normality, independence, and constant variance. Normal probability plots of residuals demonstrate excellent linearity with correlation coefficients exceeding 0.95, supporting the normality assumption. Residual versus fitted value plots show random scatter without apparent patterns, validating the independence and constant variance assumptions essential for valid statistical inference.

Model adequacy assessment employs multiple diagnostic measures including lack-of-fit testing, residual analysis, and prediction accuracy evaluation. The lack-of-fit test compares model predictions with replicated observations, yielding F-statistics of 2.1 for turning and 1.8 for milling operations, both below critical values, indicating adequate model fit. Prediction accuracy analysis shows absolute prediction errors less than 8% for confirmation experiments, validating model utility for optimization purposes.

Table 5.1: Statistical Measure

Statistical Measure	Turning Operations	Milling Operations
R-Squared	0.932	0.928
Adjusted R-Squared	0.895	0.891
Root MSE	0.109	0.108
Mean Response	0.847	0.863
Coefficient of Variation	12.9%	12.5%

VI. Optimization Results and Validation

The optimization phase synthesizes experimental results, statistical analysis, and theoretical understanding to identify parameter combinations that minimize surface roughness while maintaining manufacturing efficiency. This comprehensive optimization approach employs multiple criteria including statistical significance, practical constraints, and economic considerations to ensure industrial applicability. The validation process confirms optimization results through independent experiments and establishes prediction model accuracy for future applications.

Multi-objective optimization considerations balance surface quality requirements with productivity metrics, recognizing that optimal surface finish parameters may not coincide with maximum material removal rates. The optimization methodology employs weighted objective functions incorporating surface roughness minimization as the primary objective while considering material removal rate, tool life, and manufacturing cost as secondary objectives. This balanced approach ensures practical optimization results suitable for industrial implementation.

Taguchi's signal-to-noise ratio analysis identifies robust parameter combinations that maintain consistent performance despite process variations and noise factors. The S/N ratio calculations using "smaller-the-better" quality characteristic prioritize parameter combinations that minimize both mean surface roughness and its variability. For turning operations, the optimal S/N ratio of -10.9 dB corresponds to surface roughness of 0.285 μm with excellent repeatability across multiple measurements.

Response surface methodology supplements Taguchi optimization by providing continuous response prediction capabilities and identifying parameter interaction effects. Second-order polynomial models developed from experimental data enable prediction of surface roughness at any parameter combination within the experimental range. The response surface models exhibit excellent fit with R^2 values exceeding 0.92, validating their utility for optimization and prediction purposes.

Desirability function optimization provides a systematic approach for multi-response optimization when multiple quality characteristics require simultaneous consideration. Individual desirability functions transform each response to a 0-1 scale, while overall desirability combines individual functions through geometric mean calculations. The optimization results indicate overall desirability of 0.847 for turning operations and 0.823 for milling operations, representing excellent multi-objective performance.

Genetic algorithm optimization explores the parameter space more comprehensively than traditional methods, potentially identifying global optima that conventional techniques might miss. The genetic algorithm implementation uses population size of 100, crossover probability of 0.8, and mutation probability of 0.02. The algorithm converges to optimal solutions consistent with Taguchi results while providing confidence in global optimality through extensive search space exploration.

Confirmation experiments validate optimization results using parameter combinations not included in the original experimental design. Independent validation experiments employ optimal parameter settings identified through various optimization approaches, measuring surface roughness under controlled conditions. The confirmation results demonstrate excellent agreement with predicted values, with prediction errors ranging from 2.1% to 6.8%, well within acceptable engineering tolerances.

Robustness analysis evaluates the sensitivity of optimal parameter combinations to process variations and noise factors. Noise factor experiments introduce controlled variations in cutting fluid flow rate, workpiece hardness, and ambient temperature while maintaining optimal parameter settings. The robustness analysis indicates that optimal parameter combinations maintain superior performance despite moderate process variations, confirming their suitability for industrial applications.

Table 6.1: Optimization Method

Optimization Method	**Turning Operations**	**Milling Operations**
	Ra (μm)	S/N Ratio (dB)
Taguchi Method	0.285	-10.9
Response Surface	0.293	-10.7
Genetic Algorithm	0.287	-10.8
Desirability Function	0.291	-10.8

Economic analysis evaluates the cost implications of optimization results, considering material costs, machining time, tool costs, and quality-related expenses. The optimal parameter combinations reduce surface finishing requirements, potentially eliminating secondary operations such as grinding or polishing. Economic analysis indicates cost savings of 15-25% through improved surface quality and reduced secondary processing requirements.

Implementation guidelines provide practical recommendations for industrial adoption of optimization results. The guidelines address parameter selection procedures, quality control measures, and process monitoring requirements. Recommended implementation includes pilot production trials, operator training programs, and continuous monitoring systems to ensure sustained optimization benefits in production environments.

Table 6.2: Validation Experiment

Validation Experiment	**Predicted Ra (μm)**	**Experimental Ra (μm)**	**Prediction Error (%)**	**Repeatability (%)**
Turning - Optimal	0.295	0.285	3.4	4.2
Turning - Robust	0.342	0.329	3.8	5.1
Milling - Optimal	0.325	0.312	4.0	4.8
Milling - Robust	0.378	0.361	4.5	5.3

VII. COMPARATIVE ANALYSIS AND DISCUSSION

The comparative analysis synthesizes optimization results across different methodologies while examining the broader implications of Taguchi-ANOVA integration for CNC machining parameter optimization. This comprehensive discussion evaluates the relative merits of various optimization approaches, addresses limitations and challenges, and positions the current research within the broader context of manufacturing process optimization. The analysis provides critical insights into the practical implementation of statistical optimization methods in industrial CNC machining operations.

Methodology comparison reveals that Taguchi method offers superior experimental efficiency compared to traditional full factorial designs while maintaining statistical rigor. The L27 orthogonal array utilized in this study required only 27 experimental runs compared to 81 runs for equivalent full factorial design, representing 67% reduction in experimental effort. Despite the reduced experimentation, the Taguchi approach captured 93.2% of parameter effects, demonstrating exceptional efficiency in identifying optimal conditions for surface roughness minimization.

Statistical robustness comparison between Taguchi and response surface methodology indicates comparable optimization performance with distinct advantages for each approach. Taguchi method excels in experimental efficiency and noise factor consideration, while response surface methodology provides superior prediction capability and interaction visualization. The integration of both approaches in this study leveraged their complementary strengths, resulting in robust optimization with comprehensive statistical validation.

Parameter significance rankings demonstrate remarkable consistency across different optimization methodologies, reinforcing the reliability of experimental results. Feed rate emerged as the dominant factor in all optimization approaches, contributing 47-53% to surface roughness variation across turning and milling operations. This consistency validates the fundamental machining relationships and provides confidence in the optimization results for industrial implementation.

Surface roughness improvement analysis reveals substantial quality enhancements through optimized parameter selection. The optimal parameter combinations achieved 65% surface roughness reduction in turning operations and 62% improvement in milling operations compared to conventional parameter settings. These improvements translate to significant quality benefits including enhanced tribological properties, improved fatigue resistance, and reduced secondary processing requirements.

Manufacturing productivity impact assessment indicates that optimization results maintain reasonable material removal rates while achieving superior surface quality. The optimal parameter combinations for turning operations yielded material removal rate of 18.7 cm^3/min compared to 24.3 cm^3/min for conventional parameters, representing 23% productivity reduction. However, the elimination of secondary finishing operations more than compensates for the reduced primary machining productivity.

Tool life implications of optimization results suggest extended cutting tool durability through reduced cutting forces and improved thermal conditions. The optimal parameter combinations reduced cutting forces by 15-20% in turning

VIII. CONCLUSIONS

This study focused on optimizing CNC machining parameters to improve surface finish using Taguchi design of experiments and Analysis of Variance (ANOVA). The experimental results clearly demonstrate that machining parameters such as cutting speed, feed rate, and depth of cut significantly influence the surface roughness of the machined parts. The Taguchi method provided an efficient framework for designing experiments and identifying optimal parameter settings with a reduced number of trials. ANOVA analysis further quantified the contribution of each factor, revealing that feed rate and cutting speed were the most influential variables affecting surface finish, followed by depth of cut. The interaction effects between parameters were found to be statistically insignificant, allowing for simplified process control. Confirmation tests validated the effectiveness of the optimized parameters in reducing surface roughness, enhancing overall machining quality and productivity. These findings offer valuable guidelines for process engineers to improve surface integrity in CNC machining operations. Future work may explore the integration of multi-objective optimization techniques, such as grey relational analysis or genetic algorithms, to simultaneously optimize additional responses like tool wear and material removal rate.

REFERENCES

[1]. Montgomery, D.C. (2009). *Design and Analysis of Experiments*, 7th ed., John Wiley & Sons.

[2]. Davim, J.P. (2001). "A note on the determination of optimal cutting conditions for surface finish obtained in turning using design of experiments." *Journal of Materials Processing Technology*, 116(2–3), 305–308.

[3]. Nalbant, M., Gokkaya, H., & Sur, G. (2007). "Application of Taguchi method in the optimization of cutting parameters for surface roughness in turning." *Materials & Design*, 28(4), 1379–1385.

[4]. Suresh, P. V. S., Rao, P. V., & Deshmukh, S. G. (2002). "A genetic algorithm-based approach for optimization of surface roughness prediction model." *International Journal of Machine Tools and Manufacture*, 42(6), 675–680.

[5]. Kumar, S., & Singh, R. (2014). "Investigating the effect of machining parameters on surface roughness during CNC turning using Taguchi method." *Procedia Engineering*, 97, 250–257.