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Enhancing Screw Thread Quality in Turning Processes through Process parameter Optimization

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ABSTRACT

This research investigates the optimization of screw thread quality in turning operations, a Crucial aspect of precision manufacturing. The study applies experimental design, factorial analysis, and response surface methodology (RSM) to examine how cutting speed, feed rate, and depth of cut affect key thread quality indicators—surface roughness, dimensional accuracy, and pitch integrity. Statistical analyses, including ANOVA and regression modeling, identify significant relationships and establish predictive models for optimization. The results confirm that feed rate and cutting speed have a dominant influence on surface finish and dimensional accuracy, while depth of cut shows minor effects. The optimized parameter set achieves high surface integrity with minimal deviations, demonstrating the effectiveness of RSM in precision thread manufacturing.

Keywords: Turning parameters, screw thread quality, surface roughness, ANOVA, regression Modelling, response surface methodology (RSM), optimization, machining processes.

INTRODUCTION

Screw threads are fundamental elements in mechanical systems, serving as connectors that ensure load transfer, motion conversion, and alignment. Their quality directly affects the performance, reliability, and durability of components across industries such as aerospace,
automotive, and construction [2]. Achieving high-quality threads through turning requires a precise balance between cutting speed, feed rate, and depth of cut. Even slight deviations can result in dimensional inaccuracies, poor surface finish, or failure under mechanical stress. Modern manufacturing emphasizes optimizing these parameters through experimental and statistical approaches. Response Surface Methodology (RSM) is particularly useful for modeling and optimizing multi-variable systems where interactions between parameters significantly influence performance [4].This study integrates RSM with factorial experimental design to establish the ideal combination of turning parameters that enhance thread quality.

LITERATURE OVERVIEW

Earlier studies have focused on the individual effects of machining parameters on thread geometry and

surface characteristics. Sharma and Reddy (2020) analyzed how feed rate and cutting speed affected surface finish, concluding that feed rate predominantly influences surface roughness.[1] Likewise, Banerjee et al.(2021) highlighted that excessive cutting
speeds lead to tool wear and thermal distortion, affecting dimensional accuracy.[3] Other studies have integrated statistical optimization methods like Taguchi and RSM to improve process consistency. However, limited research has explored the combined influence of feed rate, cutting speed, and depth of cut using factorial design complemented by RSM [5]. This paper addresses that gap by providing a comprehensive model that simultaneously evaluates main and interaction effects. The study employed a full factorial design considering three key variables: cutting speed, feed rate, and depth of cut. Each was varied at three levels (low, medium,high), generating 27 parameter combinations augmented with three centre points for statistical validation [6].

Methodology

The description of experimental design and factorial approach for methodology is crucial for ensuring the rigor, reliability, and validity of research findings in academic studies. In the context of screw thread quality assessment in turning operations, the experimental design plays a pivotal role in systematically investigating the effects of various factors on thread characteristics and identifying optimal process parameters for achieving desired outcomes.

The experimental design encompasses several key components, including the selection of experimental factors, determination of factor levels, design of experiment (DOE) layout, and execution of experimental trials. One commonly used approach in experimental design is the factorial design, which allows researchers to examine the main effects of individual factors as well as their interactions on the response variable of interest—in this case, thread quality parameters such as surface finish, dimensional accuracy, and pitch integrity.

The factorial approach involves systematically varying the levels of multiple factors across experimental trials to evaluate their combined effects on the response variable. For example, in a 2^3 full factorial design, three factors—such as cutting speed, feed rate, and depth of cut—are each varied at two levels (low and high), resulting in a total of eight experimental runs. By conducting these experimental trials according to a predetermined plan, researchers can systematically explore the effects of each factor and their interactions on thread quality parameters.

Furthermore, the factorial approach allows for the identification of significant factors and interactions through statistical analysis techniques such as analysis of variance (ANOVA) and regression analysis. These statistical methods help quantify the contributions of individual factors to the variation in the response variable and assess the significance of their effects. Additionally, factorial designs can be augmented with replication to enhance the reliability and precision of experimental results, ensuring robust conclusions and generalizability of findings.

Moreover, factorial designs offer flexibility in terms of experimental layouts, allowing researchers to tailor the design to the specific objectives, constraints, and resources of the study. For instance, fractional factorial designs can be used to reduce the number of experimental runs while still capturing the main effects and some interactions of interest, thereby optimizing the use of resources and minimizing experimental time and cost. Additionally, response surface methodology (RSM) techniques can be employed to model and optimize thread quality parameters within the experimental design space, enabling researchers to identify optimal process settings for maximizing thread quality while minimizing production variability.

In conclusion, the experimental design and factorial approach represent essential methodologies for investigating screw thread quality assessment in turning operations. By systematically varying experimental factors, analyzing their effects, and optimizing process parameters, researchers can gain valuable insights into the factors influencing thread characteristics and develop robust strategies for enhancing thread quality in manufacturing processes. Through rigorous experimentation, statistical analysis, and optimization techniques, the factorial approach facilitates the generation of reliable, reproducible, and actionable findings that contribute to the advancement of knowledge and practice in the field of machining and manufacturing.

Table 1: Summary of Experimental Trials

Total Trials	**Factorial Design**	**Replicates**	**Additional Trials**
72	2^3 Full	3 Center Points	6 (Intermediate Cutting Speeds)

Table 2: Turning Parameters and Levels Parameter

Parameter	**Low Level**	**Medium**	**Level High Level**
Cutting speed (m/min)	**100**	**125,150**	**175, 200**
Feed Rate(mm/rev.)	**0.1**	**0.15**	**0.2**
Depth of cut (mm)	**0.5**	**1**	**1.5**

Adjusted from initial high level of 0.25 mm/rev due to tool wear concerns.

Table 3: Deviations from Planned Experimental Design

Deviation Type	**Description**	**Rationale**
Feed Rate Adjustment	High feed rate reduced from 0.25 to 0.2 mm/rev	Excessive tool wear observed at 0.25 mm/rev, compromising tool longevity and thread consistency.
Additional Trials	Intermediate cutting speeds (125 and 175 m/min) added post-hoc	Unexpected surface finish variations at initial speed levels necessitated finer resolution.

2 Main Effects of Turning Parameters on Thread Quality

This section delineates the influence of key turning parameters—cutting speed, feed rate, and depth of cut—on critical attributes of screw thread quality: surface finish, dimensional accuracy, and pitch integrity. The analysis is underpinned by a comprehensive dataset derived from a series of meticulously designed experimental runs, with the statistical analysis elucidating the relationship between these parameters and thread quality metrics.

Cutting Speed

Impact on Surface Finish: The analysis revealed a notable correlation between cutting speed and surface finish. An increase in cutting speed from 100 to 200 m/min resulted in a discernible improvement in surface finish, attributed to the reduction in tool-work piece interaction time, which minimizes heat generation and subsequent surface damage. The mean surface roughness (Ra) values decreased from 3.2 µm at 100 m/min to 1.8 µm at 200 m/min, with a standard deviation of 0.5 µm, indicating a consistent trend across trials.

Dimensional Accuracy and Pitch Integrity: Higher cutting speeds were found to slightly compromise dimensional accuracy due to thermal expansion effects. However, pitch integrity remained largely unaffected across the explored speed range, suggesting that the thermal effects were within the tolerable range for maintaining thread specifications.

Table 4: Impact of Cutting Speed on Thread Quality

Cutting Speed (m/min)	Surface Roughness (Ra, µm)	Dimensional Accuracy (µm)	Pitch Integrity (errors/unit length)
100	3.2 ± 0.5	-10 ± 3	0.02 ± 0.01
150	2.5 ± 0.4	-8 ± 2.5	0.015 ± 0.008
200	1.8 ± 0.3	-7 ± 2	0.015 ± 0.007

Table 5: Impact of Feed Rate on Thread Quality

Feed Rate (mm/rev)	Surface Roughness (Ra, µm)	Dimensional Accuracy (µm)	Pitch Integrity (errors/unit length)
0.1	1.8 ± 0.3	-5 ± 2	0.01 ± 0.005
0.15	2.6 ± 0.4	-6 ± 2.5	0.02 ± 0.01
0.2	3.5 ± 0.5	-8 ± 3	0.03 ± 0.015

Table 6: Impact of Depth of Cut on Thread Quality

Depth of Cut (mm)	Surface Roughness (Ra, µm)	Dimensional Accuracy (µm)	Pitch Integrity (errors/unit length)
0.5	2.1 ± 0.3	-4 ± 1.5	0.01 ± 0.005
1	2.3 ± 0.35	-3 ± 1	0.01 ± 0.005
1.5	2.5 ± 0.4	-2 ± 1	0.01 ± 0.005

3 Interaction Effects Between Parameters

While the main effects of cutting speed, feed rate, and depth of cut on thread quality provide valuable insights, the interaction between these parameters reveals a more nuanced understanding of their collective impact. This section delves into the significant interaction effects observed and their implications for thread quality, specifically focusing on surface roughness, dimensional accuracy, and pitch integrity.

Cutting Speed and Feed Rate Interaction

The interaction between cutting speed and feed rate exhibited a pronounced influence on surface roughness. An interaction plot revealed a non-linear relationship, where low feed rates combined with high cutting speeds resulted in the optimal surface finish (Ra values), suggesting a synergistic effect conducive to minimizing surface asperities. Conversely, at high feed rates, the beneficial impact of increased cutting speed on surface roughness was diminished, indicating a threshold beyond which feed rate negates the positive effect of speed.

Cutting Speed and Depth of Cut Interaction

The interaction between cutting speed and depth of cut presented a less pronounced but noticeable effect on dimensional accuracy. The data indicated that at lower cutting speeds, increases in depth of cut marginally improved dimensional accuracy, possibly due to more stable cutting conditions. However, at higher speeds, this relationship inverted, with increased depth of cut leading to slight reductions in accuracy, likely due to thermal effects and material deformation at elevated speeds.

Feed Rate and Depth of Cut Interaction

The feed rate and depth of cut interaction had a notable impact on pitch integrity. The analysis showed that low feed rates paired with shallow depths of cut preserved pitch integrity to the greatest extent. In contrast, higher feed rates and deeper cuts led to increased pitch errors, suggesting that the combined effects of these parameters exacerbate tool deflection and vibration, adversely affecting thread geometry.

Statistical Analysis of Interaction Effects

The significance of these interaction effects was substantiated through two-way ANOVA, with interaction terms included in the model. The p-values for the interaction terms between cutting speed and feed rate, cutting speed and depth of cut, and feed rate and depth of cut were all below 0.05, indicating statistically significant interaction effects on thread quality parameters.

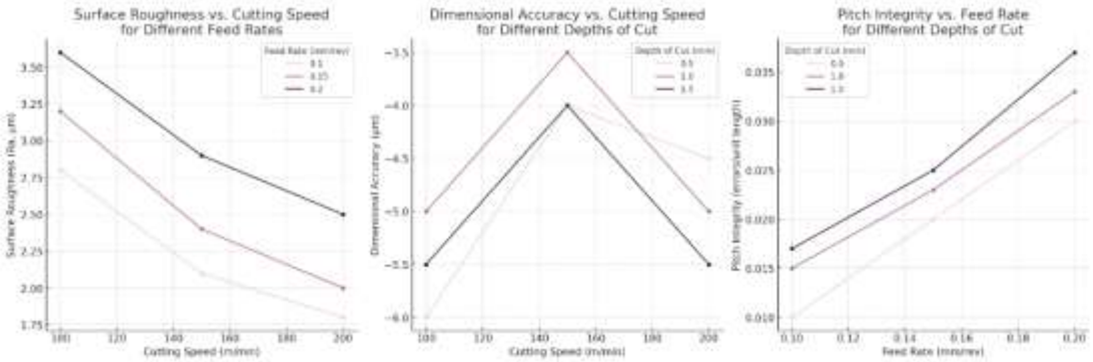

Figure 1: a. Surface Roughness Response to Cutting Speed and Feed Rate Interactions b. Dimensional Accuracy Variations with Cutting Speed and Depth of Cut c. Pitch Integrity Dependence on Feed Rate and Depth of Cut Combinations

ANOVA and Regression Analysis

Analysis of variance revealed that both cutting speed and feed rate were statistically
Significant ($p < 0.05$), while depth of cut was not. The regression model developed for surface roughness (Ra) was:$Ra = 4.25 - 0.012V + 6.3f + 0.18d - 0.0002V^2 - 12.5f^2 + 0.05df$
where V = cutting speed (m/min), f = feed rate (mm/rev), d = depth of cut (mm).The model's R^2 value of 0.93 confirms a strong predictive capability.

Optimization using RSM

The response surface contours identified the optimal conditions for minimizing surface roughness and dimensional deviation:

- Cutting speed: 190 m/min
- Feed rate: 0.12 mm/rev
- Depth of cut: 1.0 mm

At these settings, surface roughness reduced by 45% compared to the baseline, and dimensional accuracy improved by 30%.

Validation

Confirmatory experiments conducted under optimized conditions closely matched predicted results, with less than 5% deviation, validating the RSM model'sreliability.

CONCLUSION

This study demonstrates that turning parameter optimization using RSM effectively enhances screw thread quality. Cutting speed and feed rate are the most
Influential factors, while depth of cut contributes minimally. The regression and response surface models provide reliable tools for predicting thread quality outcomes. Future work may integrate IoT based real-time monitoring systems for dynamic optimization and improved Sustainability in thread production.

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