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Investigation of Process Parameters on Milling Operation to Optimize the Response Parameter Over Cut Using DOE Method

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A B S T R A C T

The study investigates the influence of process parameters on milling operations to optimize the response parameter overcut (OC) using the Design of Experiments (DOE) method. Signal-to-noise (S/N) ratio analysis was employed to evaluate OC under the "smaller is better" criterion. The parameters analyzed included spindle speed, feed rate, and depth of cut (DOC). S/N ratios for OC across experimental runs were calculated and tabulated in current study, revealing critical insights into process optimization. Rank determination using delta calculations, presented in present research, identified DOC as the most influential parameter, followed by feed rate and spindle speed. The main effect plot for the OC response visually confirmed these findings, highlighting the dominant impact of DOC. The results indicated that increasing DOC led to a substantial effect on overcut, while spindle speed exhibited the least influence. Additionally, the S/N ratio plot corroborated these observations, showing the highest profile for DOC and the lowest for spindle speed. This research demonstrates the efficacy of DOE methodology in isolating and ranking significant parameters in milling operations. By identifying the optimal conditions for minimizing OC, the study provides valuable insights for enhancing machining precision and operational efficiency in milling processes.

Keywords: Al 6061, milling operation, Taguchi method, signal to noise ratio, over cut

Introduction

In today's competitive industrial climate, precision and efficiency in manufacturing processes are essential for maintaining market relevance. Among these processes, CNC machining stands out as a cornerstone for producing high-precision components across various sectors. Industries such as aerospace, automotive, and power generation heavily rely on CNC machining to fabricate parts with intricate geometries, tight tolerances, and consistent quality. For small and medium-sized enterprises (SMEs), which often operate under stringent resource constraints, CNC machining offers a viable solution to meet the demands of high-precision manufacturing. However, the efficient utilization of CNC technology requires careful parameter optimization to ensure a balance between productivity and quality, especially in high-speed milling applications.

The Role of CNC Machining in Modern Manufacturing

CNC machining has revolutionized manufacturing by providing a level of precision and repeatability that manual machining cannot achieve. Its ability to handle complex geometries and thin-walled components has made it indispensable for SMEs producing critical components. High-speed CNC milling, in particular, has gained popularity due to its ability to combine speed with precision. However, this capability brings its challenges, as machining at high speeds can lead to increased tool wear, surface irregularities, and inconsistencies in dimensional accuracy.

For CNC milling to be effective, precise control of key parameters such as spindle speed, feed rate, depth of cut, and cutting insert type is required. These parameters directly influence machining outcomes, including material removal rate (MRR), surface roughness (Ra), tool wear, and overcut (OC). Inconsistent or suboptimal parameter selection can lead to inefficiencies, increased operational costs, and compromised product quality, making parameter optimization a critical aspect of CNC machining.

Challenges in Parameter Selection

Traditionally, CNC machining parameter selection has relied on the expertise of machine operators or conservative recommendations from tool-maker handbooks. While these approaches have provided satisfactory results in the past, they often lack the precision and adaptability required for modern high-speed machining environments. Operator-dependent parameter selection is inherently subjective and prone to inconsistencies, whereas tool-maker guidelines are typically conservative and may not account for the specific requirements of advanced materials or machining conditions.

The challenges become even more pronounced when machining materials like AL6061 alloy, a widely used aluminum alloy known for its excellent machinability, strength-to-weight ratio, and corrosion resistance. AL6061 is commonly employed in industries where lightweight and durable materials are essential, such as aerospace and automotive. However, machining this alloy at high speeds poses unique difficulties, including material adhesion to cutting tools, rapid tool wear, and potential surface damage. These issues necessitate a scientific, data-driven approach to parameter optimization.

The Importance of Optimization in CNC Milling

Effective parameter optimization in CNC milling involves striking a delicate balance between competing objectives. For instance, maximizing MRR is crucial for reducing production time and costs, but it often comes at the expense of surface quality and tool life. Conversely, achieving fine surface smoothness typically requires lower cutting speeds and feed rates, which can increase machining time and operational costs. Similarly, minimizing overcut is essential for ensuring dimensional accuracy, but it can be challenging to achieve alongside other performance goals.

Given these trade-offs, a multi-objective optimization framework is required to simultaneously address all critical performance measures. Such a framework enables manufacturers to identify parameter combinations that achieve a balanced compromise between conflicting objectives, thereby enhancing overall process efficiency and product quality.

Advances in Optimization Techniques

Recent advancements in optimization techniques have opened new possibilities for improving CNC machining performance. Multi-criteria decision-making (MCDM) approaches, in particular, have gained traction for their ability to evaluate multiple parameters and performance metrics simultaneously. Among these, the Combined Compromise Solution (COCOSO) method has emerged as a promising tool for parameter optimization. COCOSO integrates multiple criteria into a single evaluation framework, allowing manufacturers to derive balanced and scientifically validated parameter settings.

The integration of COCOSO with Taguchi-based Design of Experiments (DOE) further enhances its utility. The Taguchi method is a robust experimental design technique that systematically organizes the testing process to maximize the amount of useful information obtained from a limited number of experiments. By coupling Taguchi DOE with the COCOSO method, it becomes possible to efficiently analyze the effects of various machining parameters on critical performance metrics and identify the optimal parameter configuration.

The Role of AL6061 Alloy in Industrial Applications

The selection of AL6061 alloy as the material of focus for this study is not coincidental. AL6061 is widely used in applications requiring a combination of strength, corrosion resistance, and machinability. Its versatility makes it a preferred choice in sectors such as aerospace, automotive, and electronics. However, machining AL6061 alloy presents unique challenges, particularly at high speeds. The material's tendency to adhere to cutting tools can lead to rapid tool wear and poor surface quality, making parameter optimization even more critical.

Research Objectives and Methodology

This research aims to address the challenges of parameter optimization in high-speed CNC vertical milling of AL6061 alloy by employing a systematic, data-driven approach. The study combines Taguchi-based DOE and the COCOSO MCDM method to analyze the effects of spindle speed, feed rate, depth of cut, and cutting insert type on key performance metrics, including MRR, Ra, and OC. The primary objectives of the research are as follows:

To investigate the individual and combined effects of machining parameters on MRR, Ra, and OC.

To identify the optimal parameter configuration that balances these competing objectives.

To provide a decision-making framework that can guide SMEs in improving their machining processes.

The Taguchi method is used to design a set of experiments that systematically vary the machining parameters across a defined range. Performance data collected from these experiments are then analyzed using the COCOSO method, which evaluates each parameter combination against the selected performance metrics. The outcome of this analysis provides a scientifically validated parameter configuration that meets the dual objectives of efficiency and quality.

Significance of the Research

The findings of this research have significant implications for SMEs engaged in precision manufacturing. By providing a systematic and repeatable approach to parameter optimization, this study reduces the reliance on subjective judgment and minimizes human error. The use of advanced optimization techniques like COCOSO also aligns with the principles of Industry 4.0, where data-driven methodologies and intelligent systems are transforming traditional manufacturing processes.

Moreover, this research contributes to the broader field of automated manufacturing by demonstrating the applicability of MCDM methods in optimizing machining parameters. The integration of Taguchi DOE and COCOSO provides a scalable and adaptable framework that can be extended to other materials and machining processes, paving the way for more efficient and autonomous production systems.

Literature Review

With a physical vapour deposition-coated carbide tool and various cutting settings, Kasim et al. (2013) examined tool wear during Inconel 718 ball-nose end-milling. Large radial depth-of-cut wears tools. A mathematical model predicted pitting (notching and flaking) site, determining the maximum cutting load. Predicted pitting model and actual notching/flaking were within 6%.

Kuram and Ozcelik (2013) studied ball-nose end-mill micro-milling aluminum using experiments, modeling, and mono and multi-objective optimization. The Taguchi method examined how spindle speed, feed per tooth, and depth-of-cut effect tool wear, force, and surface roughness. Aluminium's ductility causes plastically deformed workpiece surfaces. First-order models for micro-milling aluminum were created using experimental data with minor errors. Optimization model used Taguchi's signal-to-noise ratio to minimize answers. The responses were optimized simultaneously using gray relational analysis.

CNC machine calibration is time-consuming and expensive, according to Armin Afkhamifar et al. (2016). The designer may investigate error sources to make the CNC machine more reliable and faster to tune. Variational and finite element analysis of geometrical features predict tool tip position error.

Radu Eugen Breaz et al. explored a component class decision-making process for CNC milling, robot milling, and additive manufacturing (DMLS) in 2017. AHP was used to choose between three production processes. Clear, linguistic variable-based AHP criteria. The last ones extracted measurable AHP data using fuzzy inference. An area was addressed with the proposed method.

Tungsten carbide micro milling PCD micro end mill tool wear is tested by Xian Wu et al. (2018). Checking tool wear characteristics and methods. Results show that PCD tool wear is concentrated on the tip and creates a triangular bottom belt. Sticky, micro chipping, and abrasive wear are significant mechanisms. PCD tool wear raises cutting pressures, brittlely fractures tungsten carbide, and causes milled surface defects. A reverse cone is formed by transferring the worn PCD tool tip to the machined groove.

Milling cutting temperatures impact tool wear, size and form tolerances, and residual stresses, according to Karaguzel and Budak (2018). Rotary tools create intermittent operations and transient thermal loadings, making milling cutting temperature forecast and monitoring challenging. This study provides novel milling cutting tool temperature modeling and measurement methodologies. The model predicts how milling conditions affect cutting temperatures, particularly tool temperature and radial depth of cut. New measurement method and literature data confirm model predictions.

In 2018, Song Ren et al. studied Kirchhoff plate-multi pocket construction. The authors' subdomain decomposition method gives semi-analytical vibration solutions for this thin-walled design. A dynamic cutting model accounts for cutting position and vibration to represent milling force. Combining the vibration and dynamic cutting models creates the thin wall milling process's governing equation, which fully accounts for dynamic qualities. When cutting discretely, milling thin-walled constructions is stable under the quasi static hypothesis. Semi-discrete analysis analyzes thin wall milling stability. Critical depth of cut is inversely related to mode shape square for each mode. Additionally, multimode and mode coupling effects on milling stability are explored.

A geometrical model for flank-milling surface topography employing circle-segment end mills was developed by G. Urbikain et al. (2018). This time-domain model includes the most important cutting mechanical and kinematical parameters: tool shape, feed rate, radial immersion, and run out. Includes 5-axis tool orientation angles. Experimental data were used to verify the model in a machined aluminum Al7075T wall. This knowledge-based system optimizes and controls production parameters for manufacturers and suppliers.

Machine Overview

On the other hand, machine aspects are also taken into consideration in this research endeavor. This is in addition to the fact that the input parameters for the current study were chosen from previous research work. Choosing a straightforward rectangular bar cut is the first step in the process of cutting the bar with the CNC milling machine. Within the scope of this chapter, each and every one of the machine's technical parameters, in addition to its limitations, are taken into consideration. During the course of this inquiry, the MAXIMIL MATB CNC MILLING machine was employed more than once. In order to accomplish the goals of this research activity, the industrial form of AL-Alloy-6061 has been specifically chosen. The components of the apparatus have been put in place at the JEC in Jaipur.

Figure 1 CNC milling test setup used in present study

For the purpose of this inquiry, the design of experiment (DOE) methodology that is commonly referred to as the "TAGUCHI" method was utilized. When it comes to CNC milling, the metal removal rate (MRR) and the surface roughness quality evaluation are both regarded to be important performance indicators. In CNC MILLING operations, surface roughness is a measurement of the degree of accuracy and geometrical correctness, whereas MRR is used to determine the economics of machining and the speed of production. Surface roughness is a measure of degree of precision.

Factor and Level

Three key process parameters or factors—Spindle Speed, Feed Rate, and Depth of Cut (DOC)—are evaluated to determine their effect on surface roughness in CNC milling. These factors play a crucial role in defining the machining efficiency, surface finish, and quality of the final product. Through the Design of Experiments (DOE) method, specific levels for each factor are established, allowing for a structured approach to test various combinations and analyze their impact on surface roughness.

Factor I: Spindle Speed

Spindle speed is the rotational speed of the CNC milling machine's spindle, measured in revolutions per minute (RPM). In this study, spindle speed is varied across four levels: 2000, 2250, 2500, and 2750 RPM. Spindle speed is an essential factor because it influences the rate of material removal and affects the temperature at the cutting interface. Higher speeds may lead to a smoother surface due to reduced tool vibration, but excessive speeds can cause thermal deformation, impacting surface finish negatively.

Factor II: Feed Rate

Feed rate is the speed at which the cutting tool advances into the material, measured in millimeters per revolution (mm/REV). The levels of feed rate chosen in this study are 60, 70, 80, and 90 mm/REV. The feed rate significantly affects the surface roughness, as higher feed rates may lead to rougher surfaces due to increased cutting force and tool vibrations. On the other hand, lower feed rates can produce finer finishes but may increase machining time.

Factor III: Depth of Cut (DOC)

Depth of Cut (DOC) refers to the thickness of material removed in one pass, measured in millimeters (mm). The levels for DOC in this study are set at 0.3, 0.4, 0.5, and 0.6 mm. DOC influences surface roughness, tool wear, and power consumption. Higher DOC values allow for quicker material removal but can lead to increased tool wear and rougher surfaces, whereas lower DOC values generally yield smoother finishes with longer tool life.

By examining these factors at their respective levels, the DOE method facilitates an understanding of their combined and individual effects on surface roughness. This analysis is essential for optimizing CNC milling operations to achieve the desired surface quality while maintaining efficient machining parameters. The orthogonal array develop for these factors were present in table 1.

Table 1 Orthogonal Array L16 developed in present study

Run	**Spindle Speed**	**Feed Rate**	**DOC**	Over Cut
1	2000	60	0.3	0.271
2	2000	70	0.4	0.375
3	2000	80	0.5	0.518
4	2000	90	0.6	0.702
5	2250	60	0.4	0.497
6	2250	70	0.3	0.289
7	2250	80	0.6	0.457
8	2250	90	0.5	0.638
9	2500	60	0.5	0.501
10	2500	70	0.6	0.734
11	2500	80	0.3	0.338
12	2500	90	0.4	0.857
13	2750	60	0.6	0.546
14	2750	70	0.5	0.668
15	2750	80	0.4	0.646
16	2750	90	0.3	0.466
Unit	**RPM**	**mm/Rev**	**mm**	**mm**

In this study, an Orthogonal Array (OA) L16 was employed to analyze the impact of CNC milling process parameters on surface roughness. The L16 OA, part of the Taguchi method in Design of Experiments (DOE), is a powerful tool that allows for the efficient exploration of multiple factors at multiple levels without requiring an exhaustive number of experimental trials. By structuring the experiments in an orthogonal array, interactions between parameters can be investigated systematically and with reduced experimental effort. The L16 OA used here includes 16 experimental runs, each with a unique combination of levels for three key factors: Spindle Speed, Feed Rate, and Depth of Cut (DOC). The parameters and their levels are arranged such that all combinations are adequately represented across the trials, facilitating a balanced assessment of each factor's effect on surface roughness. This structured approach minimizes variation due to uncontrolled factors and enables an accurate analysis of the impact of the controlled parameters on surface quality. In Table 1, each row represents a unique run with specified values for Spindle Speed (in RPM), Feed Rate (in mm/Rev), and DOC (in mm). For each run, the resulting surface roughness (in micrometers) is measured, providing a dataset to assess how changes in process parameters affect surface finish. For example, Run 1 has a Spindle Speed of 2000 RPM, Feed Rate of 60 mm/Rev, and DOC of 0.3 mm, resulting in a surface roughness of 2.25 micrometers. By examining the results across all 16 runs, the study identifies the optimal parameter settings for minimizing surface roughness. Using the L16 OA not only enhances the study's efficiency but also ensures reliable and statistically robust conclusions. This approach allows the identification of parameter combinations that produce the desired surface quality, which is essential for optimizing CNC milling operations.

Result and Discussion

An examination of the signal-to-noise ratio was performed for the response over cut (OC) utilizing the smaller is better option. Specifically, the S.N ratio was included in table 2. It is possible to determine the most important input element that is responsible for OC enhancement by using the S/N ratio. Finding the delta for the purpose of rank identification is made easier with the assistance of individual signal to noise ratio parameters. The rank identification for the response OC was present in table 5.5. According to table 1, the factor that was the most important was the depth of cut, followed by the feed rate, and the one that was the least important was the spindle speed. The MRR response effect plot was displayed in figure 2 for your viewing pleasure.

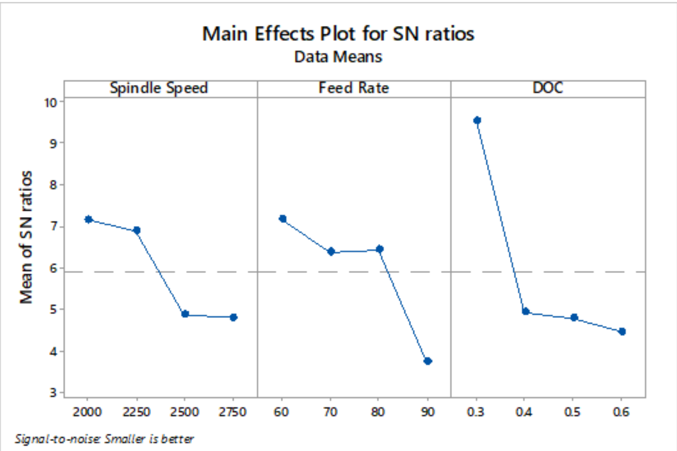

Figure 2 S/N ratio analysis using smaller is better option

From the analysis of S/N ratios, the optimal parameter combination for achieving the lowest surface roughness appears to be a Spindle Speed of 2750 RPM, Feed Rate of 60 mm/Rev, and DOC of 0.3 mm. This combination yields a lower S/N ratio, indicating minimal surface roughness. This result aligns with the theoretical understanding that a higher spindle speed, lower feed rate, and lower depth of cut generally promote a smoother surface finish in milling operations.

Table 2 Rank measurement using delta calculation for OC response

Level	Spindle Speed	Feed Rate	DOC
1	7.162	7.168	9.544
2	6.89	6.373	4.932
3	4.863	6.433	4.781
4	4.797	3.737	4.454
Delta	2.365	3.431	5.09
Rank	3	2	1

Conclusion

The investigation of milling operation parameters—spindle speed, feed rate, and DOC—using the DOE method revealed significant findings regarding their impact on overcut (OC). Analysis of the S/N ratio confirmed that DOC has the most substantial effect on minimizing OC, followed by feed rate and spindle speed. This ranking was validated by the delta values calculated in present study, where DOC achieved the highest delta and rank, emphasizing its critical role in process optimization. Visual assessments through main effect plots for the OC response and S/N ratio provided further confirmation. Current study demonstrated that DOC exhibits the steepest slope, indicating its dominant influence on OC. Similarly, the S/N ratio plot reinforced the findings, showing the highest profile for DOC and the lowest for spindle speed. The results highlight that careful selection and optimization of DOC can significantly reduce overcut, thereby improving machining precision. Feed rate also plays a notable role, though to a lesser extent, while spindle speed has minimal impact. These findings underscore the importance of prioritizing DOC in parameter optimization strategies for milling operations. In conclusion, this study validates the DOE approach as an effective tool for parameter analysis and optimization in milling. By identifying and ranking the significance of individual parameters, this research contributes to enhancing operational efficiency and machining quality in industrial applications. Future work may explore the integration of advanced optimization techniques or the application of these findings to diverse materials and machining conditions..

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