Technical Report

Optimization of Surface Finish in CNC Milling of AL6061 Using the Taguchi Method

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Abstract

In modern manufacturing, particularly in the aerospace and defence sectors, the functional performance and reliability of components are critically dependent on their surface quality. This project presents a systematic investigation into the optimization of CNC milling parameters to achieve a minimal surface roughness (Ra) on AL6061 aluminium alloy. The Taguchi method, a robust statistical technique for Design of Experiments (DOE), was employed to analyse the influence of three key machining parameters: cutting speed, feed rate, and depth of cut, each at three distinct levels.

An L9 orthogonal array was utilized to structure the experimental plan, minimizing the number of required trials to nine. These trials were conducted on a BFW BMV 35+ CNC milling machine. The surface roughness of each machined sample was measured using a high-precision Bruker Contour GT non-contact optical profilometer. The experimental results were then transformed into Signal-to-Noise (S/N) ratios using the "smaller-the-better" quality characteristic to evaluate the effect of each parameter.

The analysis revealed that the feed rate is the most dominant factor influencing surface roughness, followed by cutting speed and depth of cut. The optimal combination of parameters for achieving the minimum surface roughness was determined to be a cutting speed of 6000 rpm, a feed rate of 240 mm/min, and a depth of cut of 0.2 mm. This study successfully demonstrates the efficacy of the Taguchi method as an efficient and cost-effective approach for process optimization in precision manufacturing.

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1. Introduction

1.1. Background and Importance of Surface Finish

Surface finish is a critical attribute of engineered components that defines the nature of a machined surface, including its texture, lay, and waviness. In precision industries such as aerospace, automotive, and defence, the quality of a component's surface directly impacts its functional performance, including its wear resistance, fatigue strength, corrosion resistance, and ability to retain lubricant. A poor surface finish can lead to increased friction, stress concentration points, and ultimately, premature component failure. Therefore, controlling and optimizing surface finish is not merely an aesthetic consideration but a fundamental requirement for ensuring product quality and reliability.

1.2. CNC Machining and Process Parameters

Computer Numerical Control (CNC) machining is an automated manufacturing process that utilizes pre-programmed computer software to dictate the movement of factory tools and machinery. CNC milling, in particular, uses a rotating multi-point cutting tool to progressively remove material from a workpiece. The final quality of the machined surface is highly dependent on a set of controllable process parameters, primarily:

- **Cutting Speed (Vc):** The speed at which the cutting tool rotates.
- **Feed Rate (f):** The speed at which the workpiece is fed towards the cutting tool.
- **Depth of Cut (ap):** The depth of material removed in a single pass.

1.3. Problem Statement and Objectives

The conventional approach to determining optimal machining parameters often involves a time-consuming and costly trial-and-error process. This project aims to address this inefficiency by employing a structured statistical method.

The primary objectives of this study are:

1. To investigate the effect of cutting speed, feed rate, and depth of cut on the surface roughness of AL6061 alloy during CNC milling.
2. To apply the Taguchi Design of Experiments (DOE) methodology to find the optimal combination of these parameters that minimizes surface roughness.
3. To determine the relative significance of each machining parameter on the final surface quality.

2. Theoretical Background & Methodology

2.1. Machining Parameters Affecting Surface Roughness

Theoretically, surface roughness is a direct function of the tool geometry and the feed rate. However, in practice, other factors such as cutting speed, depth of cut, tool wear, and machine vibrations also play a significant role. Higher cutting speeds can sometimes improve finish due to thermal softening, while higher feed rates almost always degrade it by creating deeper tool marks. The depth of cut has a comparatively minor, yet still significant, effect.

2.2. Introduction to Design of Experiments (DOE)

Design of Experiments is a powerful statistical tool used to systematically plan, conduct, and analyse experiments. It allows researchers to study the effect of multiple input variables on an output variable simultaneously, making the experimental process efficient and scientifically rigorous.

2.3. The Taguchi Method

Developed by Dr. Genichi Taguchi, this method is a robust DOE technique focused on improving quality by making a process insensitive to sources of variation. Its key features include:

- **Orthogonal Arrays (OAs):** These are balanced experimental design matrices that allow for the study of multiple factors with a minimal number of trials. For this project, an L9 OA was chosen.
- **Signal-to-Noise (S/N) Ratio:** This metric is used to measure the robustness of the process. It consolidates multiple data points into a single value that represents the amount of variation present. For minimizing surface roughness, the **"smaller-the-better"** quality characteristic is used, defined by the formula:

$$\textbf{S/N ratio} = -10 \log_{\{10\}} \left(\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right)$$

(where 'n' is the number of measurements in a trial and 'y' is the measured value (Ra).)

3. Experimental Setup and Procedure

3.1. Machine and Tooling Specifications

- **CNC Machine:** Gaurav+ (BFW BMV 35+) 3-axis Vertical Machining Center.
- **Tool:** 6 mm solid carbide flat end mill.

3.2. Workpiece Material Properties

- **Material:** Aluminium 6061 (AL6061), a precipitation-hardened aluminium alloy.
- **Properties:** Excellent machinability, high strength-to-weight ratio, density of 2.70 g/cm^3, and hardness of 95 HB.

3.3. Measurement System

- **Instrument:** Bruker Contour GT non-contact optical profilometer. This high-precision instrument was used to measure the average surface roughness (Ra) in micrometers (μm).

3.4. Design of Experiment

The experiment was designed using an L9 orthogonal array to study three parameters at three levels each.

Table 1: Machining Parameters and Their Levels

Parameter	Level 1	Level 2	Level 3
Speed (rpm)	4200	5400	6000
Feed (mm/min)	240	420	600
Depth of Cut (mm)	0.2	0.4	0.5

3.5. Experimental Procedure

1. The AL6061 workpiece was securely clamped onto the CNC machine bed.
2. The nine experimental runs were conducted as per the L9 orthogonal array design.
3. For each run, the surface roughness (Ra) was measured at five different locations to ensure statistical consistency.
4. The average Ra value and the S/N ratio for each run were calculated.

(refer to Appendix A)

4. Results and Discussion

4.1. Experimental Data

The average surface roughness (Ra) and the calculated S/N ratio for each of the nine trials are presented below.

Table 2: Taguchi L9 Experimental Results

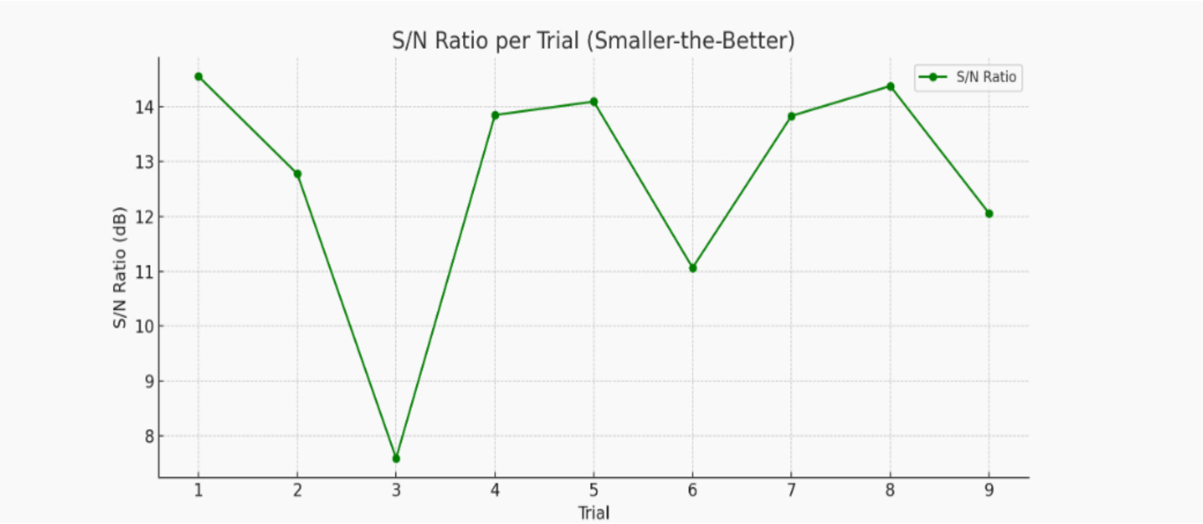
Trial	Speed (rpm)	Feed (mm/min)	Depth (mm)	Avg. Ra (µm)	S/N Ratio (dB)
1	4200	240	0.2	0.1857	14.62
2	4200	420	0.4	0.2297	12.78
3	4200	600	0.5	0.4170	7.60
4	5400	240	0.4	0.2020	13.89
5	5400	420	0.5	0.1970	14.11
6	5400	600	0.2	0.2797	11.07
7	6000	240	0.5	0.2033	13.84
8	6000	420	0.2	0.1905	14.40
9	6000	600	0.4	0.2495	12.06

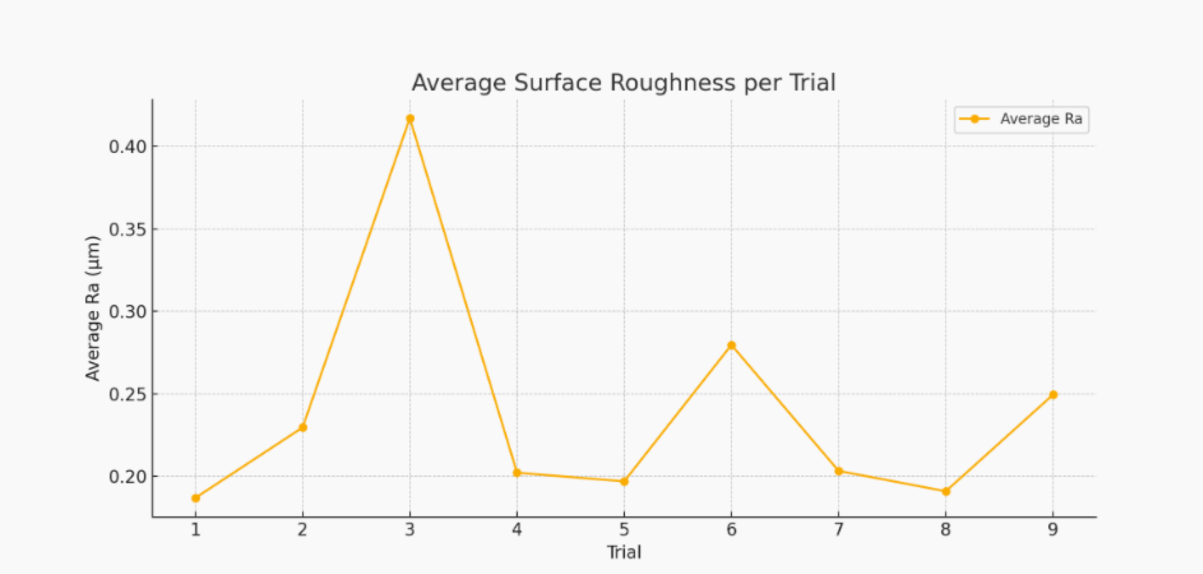
(refer to Appendix B)

4.2. Analysis of Signal-to-Noise (S/N) Ratios

The main effect plots for the S/N ratios are used to determine the optimal level for each parameter. A higher S/N ratio corresponds to a better quality characteristic (lower roughness).

Graph 1: Main Effects Plot for S/N Ratios





4.3. Effect of Machining Parameters on Surface Roughness

- **Feed Rate:** The analysis clearly shows that feed rate has the most significant impact. The S/N ratio drops sharply as the feed rate increases from 240 mm/min to 600 mm/min, indicating that a lower feed rate is crucial for a better surface finish.
- **Cutting Speed:** A higher cutting speed resulted in a better surface finish. The S/N ratio increased as the speed went from 4200 rpm to 6000 rpm.
- **Depth of Cut:** This parameter had the least effect among the three. A lower depth of cut (0.2 mm) yielded a slightly better finish.

4.4. Determination of Optimal Parameters

Based on the S/N ratio analysis (selecting the level with the highest S/N ratio for each parameter), the optimal combination for minimum surface roughness is:

- **Speed:** 6000 rpm (Level 3)
- **Feed:** 240 mm/min (Level 1)
- **Depth of Cut:** 0.2 mm (Level 1)

5. Error Analysis and Validation

5.1. Potential Sources of Error

While the experiment was conducted under controlled conditions, several potential sources of error must be acknowledged:

- **Tool Wear:** Progressive wear of the cutting tool across the nine trials could have slightly altered the cutting geometry and affected the surface finish.
- **Machine Vibrations:** Inherent vibrations in the machine tool, especially at higher speeds, can introduce micro-chatter marks on the surface.
- **Material Inhomogeneity:** Minor variations in the microstructure of the AL6061 workpiece could lead to localized differences in machinability.
- **Measurement Error:** Although a high-precision instrument was used, factors like surface contaminants (dust, oil) could introduce minor inaccuracies in Ra readings.

5.2. Validation of Results

A confirmation experiment using the identified optimal parameter settings should be conducted to validate the findings. The resulting surface roughness from this confirmation run would be compared against the theoretically predicted value to verify the effectiveness of the optimization process.

6. Conclusion and Future Scope

6.1. Conclusion

This project successfully applied the Taguchi method to optimize the CNC milling parameters for minimizing surface roughness on AL6061 alloy. It was conclusively determined that feed rate is the most influential parameter. The optimal process parameters were identified as a high cutting speed (6000 rpm), a low feed rate (240 mm/min), and a low depth of cut (0.2 mm). The study highlights the power of statistical DOE techniques in improving manufacturing processes efficiently and scientifically.

(refer to Appendix C)

6.2. Future Scope

Further research could expand upon this study in several ways:

- Conducting a full Analysis of Variance (ANOVA) to quantify the percentage contribution of each parameter.
- Investigating the effect of other parameters, such as tool nose radius and coolant application.
- Studying the effect of tool wear on surface roughness over an extended production run.
- Applying other optimization techniques like Response Surface Methodology (RSM) for a more detailed analysis.

Appendix A – Machine and Material Details

CNC Machine: Gaurav+ (BFW BMV 35+)

The CNC machining operations were carried out on a **Gaurav+ series BFW BMV 35+ vertical machining centre**, a robust 3-axis milling machine designed for high-precision industrial applications. Manufactured by **Bharat Fritz Werner (BFW)**, the BMV 35+ offers excellent rigidity, positional accuracy, and repeatability—making it suitable for detailed surface finish studies.

Machine Specifications:

- **Model**: Gaurav+ (BFW BMV 35+)
- **Spindle Speed Range**: Up to 8000 RPM
- **Table Size**: 900 mm × 450 mm
- **Positioning Accuracy**: ±5 µm
- **Spindle Power**: 5.5 – 7.5 kW
- **Controller**: Siemens/FANUC (as configured)
- **Tool Changer**: Automatic 20-tool ATC
- **Coolant System**: Flood coolant with high-pressure delivery

The Gaurav+ machine was pre-calibrated and properly aligned prior to the cutting trials. The tool used was a **6 mm solid carbide flat end mill**, clamped using a precision collet holder.

Figure: Experimental AL6061 block illustrating the nine machined 'slabs'.
(Each surface corresponds to a unique combination of cutting speed,
feed rate, and depth of cut as specified by the L9 orthogonal array.)

Workpiece Material: Aluminium 6061 (AL6061)

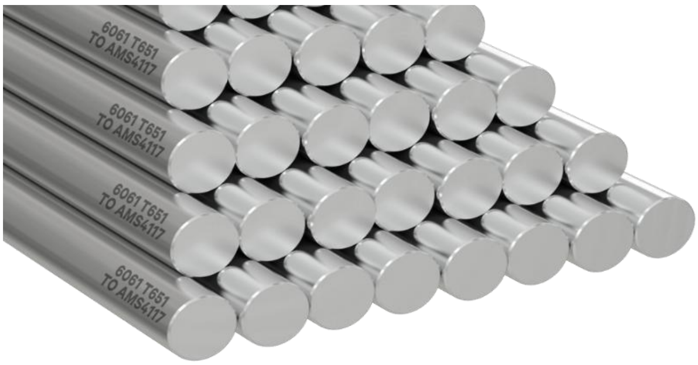
The experimental material was **AL6061**, a precipitation-hardened aluminium alloy commonly used in aerospace, automotive, and structural applications due to its excellent machinability and strength-to-weight ratio.

Material Properties:

Property	Value
Composition	Al-Mg-Si (approx. 97.9% Al)
Density	2.70 g/cm³
Hardness	95 HB (Brinell)
Ultimate Tensile Strength	310 MPa
Yield Strength	276 MPa
Thermal Conductivity	167 W/mK
Melting Point	~580–650 °C
Surface Finish Behaviour	Excellent under sharp tool and low feed rates

Why AL6061?

AL6061 offers a balanced combination of **mechanical strength, corrosion resistance, and machinability**. Its behaviour under varying speeds, feeds, and depths of cut makes it an ideal candidate for surface finish optimization studies, especially in dry or semi-dry machining environments.



Appendix B – Surface Roughness (Ra) Data

Trial	Speed (rpm)	Feed (mm/min)	Depth (mm)	Ra1 (µm)	Ra2 (µm)	Ra3 (µm)	Ra4 (µm)	Ra5 (µm)	Average Ra (µm)
1	4200	240	0.2	0.192	0.200	0.186	0.178	0.179	**0.1857**
2	4200	420	0.4	0.229	0.225	0.235	0.229	0.229	**0.2297**
3	4200	600	0.5	0.406	0.408	0.437	0.417	0.417	**0.4170**
4	5400	240	0.4	0.179	0.194	0.226	0.210	0.201	**0.2020**
5	5400	420	0.5	0.209	0.202	0.180	0.196	0.198	**0.1970**
6	5400	600	0.2	0.288	0.272	0.279	0.280	0.279	**0.2797**
7	6000	240	0.5	0.199	0.201	0.210	0.205	0.204	**0.2033**
8	6000	420	0.2	0.196	0.188	0.187	0.193	0.190	**0.1905**
9	6000	600	0.4	0.255	0.254	0.245	0.244	0.250	**0.2495**

Appendix C – Project Execution Summary

This project was completed under a condensed timeline of two working days due to academic scheduling constraints. To maximize efficiency, experimental planning and setup were executed on the first day, including the preparation of the AL6061 workpiece, selection of tool parameters, and development of the Taguchi L9 orthogonal array design. A 6 mm solid carbide end mill was used across all trials on a CNC milling machine.

On the second day, all nine machining trials were performed on a single large AL6061 block, with the toolpath carefully segmented to ensure distinct surface regions corresponding to each parameter set. Given the limited time, rather than fabricating multiple slabs for the same parameter set, each **trial was represented by a single machined slab**, and surface roughness was measured **five times at different positions on each slab**. This approach was chosen to capture local surface variations and approximate the statistical consistency of each trial without replicating the machining process.

All surface roughness (Ra) measurements were conducted using a **BRUKER Contour GT non-contact profilometer**, which enabled rapid and accurate scanning of micro-surface features. The final Ra value for each trial was calculated by averaging the readings after removing outliers, as per standard metrological practice.