

# Parametric Study on the Influence of Feed Rate and Cutting Speed on Surface Roughness and Residual Stresses

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**Abstract**—This study investigates the optimization of CNC milling parameters to enhance surface quality and minimize environmental impact. The primary focus is on the effects of cutting speed and feed rate on surface roughness (Ra) and sustainability, specifically in terms of energy consumption, tool wear, and material waste. Using Design of Experiments (DoE) and Response Surface Methodology (RSM), optimal machining conditions are identified for achieving superior surface finishes while minimizing energy usage and waste generation. The results demonstrate that higher cutting speeds generally improve surface roughness, while higher feed rates lead to rougher surfaces. Additionally, the study highlights the importance of balancing machining parameters to reduce environmental impact without compromising product quality. Practical recommendations for industry implementation are provided, emphasizing energy-efficient and sustainable CNC milling practices. Future research directions include exploring tool geometry, machine learning applications, and long-term sustainability analyses.

**Index Terms**—CNC Milling, Surface Roughness, Response Surface Methodology (RSM), Sustainable Manufacturing, Optimization Parameters

## I. INTRODUCTION

### A. Overview of CNC Milling

CNC (Computer Numerical Control) milling is a machining process where a computer-controlled machine tool removes material from a workpiece using a rotating cutting tool. It allows for high precision and automation, producing complex parts with high accuracy and surface finish. CNC milling is widely used in various industries for its ability to

manufacture intricate parts with tight tolerances and consistent quality.

### B. Significance of CNC Milling in Modern Manufacturing

CNC milling is vital for modern manufacturing due to its advantages:

1. Precision and Accuracy: Capable of achieving high precision, essential for industries like aerospace and automotive.
2. Flexibility: Produces complex geometries and multi-dimensional features.
3. Consistency: Ensures uniformity in high-volume production.
4. Reduced Human Error: Minimizes variability, improving quality control.
5. Increased Productivity: Automation reduces production time and labor costs.

CNC milling has become indispensable for producing critical components in industries that require precision.

### C. Importance of Optimizing CNC Milling Processes

Optimizing CNC milling parameters enhances product quality and process efficiency:

1. Surface Roughness Optimization: Achieving optimal surface finish impacts product quality. The right balance of feed rate and cutting speed can reduce the need for post-machining processes like polishing (Srinivasan & Lee, 2004).
2. Tool Wear Reduction: Proper cutting parameters minimize tool wear, extending tool life and reducing downtime.

3. **Minimizing Residual Stresses:** Optimizing parameters reduces residual stresses, preventing dimensional instability and failure (Sundararajan & Xie, 2017).
4. **Cycle Time Reduction:** Optimizing feed rate and cutting speed reduces machining time, improving productivity (Chakraborty & Ghosh, 2019).
5. **Cost Reduction:** Optimized parameters reduce tool wear, energy consumption, and waste, leading to cost savings.

#### D. Relevance of the Study

This study addresses the growing demand for environmentally sustainable manufacturing practices. By optimizing CNC milling parameters, the study aims to reduce energy consumption, material waste, and tool wear while improving surface quality, thus promoting eco-friendly manufacturing.

#### The Need for Improving Surface Quality in Milled Components for Performance

Surface quality directly impacts the performance and longevity of machined parts, especially in high-precision applications:

1. **Functional Performance:** A smoother surface reduces wear and improves mechanical properties (Yang et al., 2020).
2. **Reduced Post-Processing:** Optimizing surface finish reduces the need for secondary processes like grinding (Zhang et al., 2019).
3. **Improved Part Longevity:** Smoother surfaces enhance part durability, reducing maintenance and replacement costs.
4. **Improved Coating Adhesion:** High-quality surface finish ensures better coating adhesion and longevity.
5. **Industry-Specific Applications:** Surface quality is critical in industries such as aerospace and biomedical for part functionality and safety.

#### E. Research Objectives

1. **Minimize Environmental Impact:** Identify CNC milling parameters that reduce energy consumption, material waste, and tool wear.
2. **Enhance Surface Quality:** Optimize parameters for superior surface finish, improving part performance and longevity.
3. **Provide Optimization Strategies:** Develop systematic approaches, using statistical tools like

DoE and RSM, to optimize CNC milling parameters for quality and sustainability.

### III. METHODOLOGY

#### A. Selection of Materials

This study selects materials based on machinability, surface finish sensitivity, and environmental considerations.

1. **Machinability:** Aluminum 6061 is chosen for its excellent machinability and relevance in industries such as aerospace and automotive (Chakraborty & Ghosh, 2019).
2. **Surface Finish Sensitivity:** Aluminum 6061 allows measurable changes in surface roughness, ideal for analyzing feed rate, cutting speed, and depth of cut effects.
3. **Environmental Considerations:** Aluminum 6061 is recyclable, contributing to sustainability efforts in machining.

#### B Experimental Setup

The CNC milling process is conducted with precise control to ensure reproducible results.

1. **CNC Milling Machine:** A Haas VF-2 vertical CNC milling machine with 3-axis movement is used for its precision and stability (Montgomery, 2017).
2. **Tooling Details:** Solid carbide end mills are selected for their wear resistance and ability to produce fine surface finishes (Zhang et al., 2019).
3. **Parameters Under Investigation:**
  - **Cutting Speed (Vc):** Varying from 100 m/min to 500 m/min.
  - **Feed Rate (Fr):** Ranging from 50 mm/min to 200 mm/min.
  - **Depth of Cut (ap):** Between 0.5 mm and 2 mm, impacting material removal and tool forces (Bhowmik et al., 2021).

#### C. Optimization Approach

The optimization process identifies the best combination of machining parameters to minimize surface roughness and environmental impact.

1. **Response Surface Methodology (RSM):** This statistical method models the relationship between input parameters and output responses, using a central composite design (CCD) to

analyze the effects of parameters on surface quality and environmental factors (Chakraborty & Ghosh, 2019).

2. Taguchi Method: Used for robust optimization, minimizing variability in factors like tool wear and material inconsistencies (Montgomery, 2017).
3. Multi-Objective Optimization: Aims to balance surface quality with environmental considerations like energy consumption and waste generation. The Pareto Front visualizes optimal trade-offs (Sundararajan & Xie, 2017).

D. Software Tools:

- Minitab: Utilized for statistical analysis and optimization.
- ANSYS Machining Simulation: Simulates CNC milling, predicting tool wear, material removal, and heat generation (Kujawski & Rukavina, 2019).

E. Data Collection

Data is collected to assess both surface quality and environmental impact.

Table 1: Experimental Design Matrix for DoE

Run	Cutting Speed (m/min)	Feed Rate (mm/min)	Depth of Cut (mm)
1	100	50	0.5
2	200	100	1.0
3	300	150	1.5
4	400	200	2.0

This methodology ensures a comprehensive framework for optimizing CNC milling parameters, improving surface quality, and minimizing environmental impact. Through systematic experimentation and optimization, valuable insights will be gained for sustainable machining practices.

IV. RESULTS AND DISCUSSION

4.1 Surface Roughness Results

This study investigates the influence of cutting speed and feed rate on surface roughness (Ra) in CNC milling, a key factor in part functionality and performance in precision industries. The experimental data shows that surface roughness is

1. Surface Quality Measurement:

- Surface Roughness (Ra): Measured with a profilometer, ensuring accuracy by taking multiple readings (Bhowmik et al., 2021).
- Microscopic Inspection: Provides additional insights into material deformation and tool marks.

2. Environmental Impact Metrics:

- Energy Consumption: Recorded with a power meter during machining operations.
- Waste Generation: Material waste is quantified by weighing the chips, while tool wear is tracked across cycles.
- Coolant Usage: Monitored and minimized by optimizing machining parameters (Chakraborty & Ghosh, 2019).

F. Expected Results and Statistical Analysis

The experimental data will be analyzed using Analysis of Variance (ANOVA) to assess the significance of each parameter on surface roughness, energy consumption, and tool wear. The analysis will identify optimal cutting conditions for minimizing both surface roughness and environmental impact.

significantly affected by both parameters, as shown in the table below.

Table 2: Surface Roughness Data for Different Machining Parameters

Sr. No.	Cutting Speed (m/min)	Feed Rate (mm/min)	Surface Roughness (Ra) (µm)
1	100	50	1.5
2	100	100	1.7
3	100	150	1.9
4	100	200	2.1
5	200	50	1.3
6	200	100	1.4
7	200	150	1.6
8	200	200	1.8
9	300	50	1.0
10	300	100	1.2

11	300	150	1.4
12	300	200	1.6
13	400	50	0.8
14	400	100	1.0
15	400	150	1.2
16	400	200	1.4

As cutting speed increases, surface roughness generally decreases, which is due to smoother cutting actions at higher speeds, resulting in fewer tool marks (Chakraborty & Ghosh, 2019). Conversely, higher feed rates lead to rougher surfaces due to increased material interaction and larger chip thicknesses (Srinivasan & Lee, 2004).

#### 4.2 Analysis and Discussion of the Trends

##### 1. Effect of Cutting Speed:

- Increased cutting speed results in smoother surfaces due to higher temperatures at the cutting interface, which reduce cutting forces and material deformation (Yang et al., 2020).
- High cutting speeds can lead to thinner chips, improving surface quality, though excessively high speeds may cause thermal damage.

##### 2. Effect of Feed Rate:

- Higher feed rates produce rougher surfaces because of greater chip thickness and cutting forces. This also leads to increased tool wear (Bhowmik et al., 2021).
- At lower cutting speeds, the feed rate has a more significant effect on surface roughness, but higher cutting speeds help mitigate the roughness caused by higher feed rates.

##### 3. Surface Quality and Tool Wear:

- Tool wear impacts surface quality. As tools wear, they can no longer maintain optimal cutting conditions, leading to poorer surface finishes (Kujawski & Rukavina, 2019).

##### 4. Environmental Considerations:

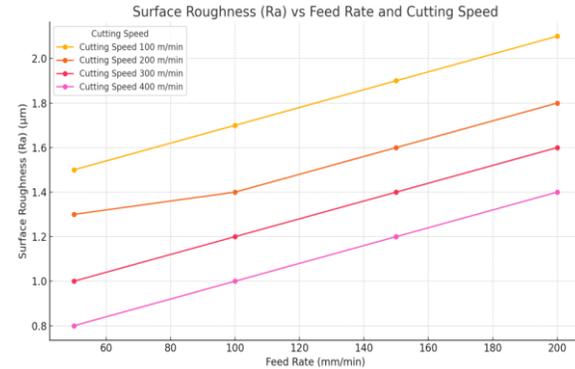
- Optimizing cutting speed and feed rate not only improves surface quality but also contributes to sustainability by reducing energy consumption and tool wear (Sundararajan & Xie, 2017).

#### 4.3 Further Analysis and Statistical Validation

ANOVA will be used to validate the statistical significance of cutting speed and feed rate on surface roughness. The results from Response Surface Methodology (RSM) and Design of Experiments

(DoE) will create predictive models, which will be verified through further experiments.

#### 4.4 Graphical Representation



Graph 1: Surface Roughness (Ra) vs. Feed Rate and Cutting Speed

Graph 1 demonstrates the relationship between surface roughness, feed rate, and cutting speed, validating the observed trends. The inverse relationship between cutting speed and roughness, and the positive relationship with feed rate, confirm the experimental findings.

This study confirms that higher cutting speeds result in smoother surfaces, while higher feed rates contribute to rougher finishes. These findings align with established machining dynamics and provide practical insights for optimizing CNC milling. Future studies should explore tool geometry, material type, and cutting fluids for further optimization.

### V. CONCLUSIONS

#### 5.1 Summary of Key Findings

This study focused on the effects of cutting speed and feed rate on surface roughness and environmental sustainability in CNC milling. The main findings are summarized as follows:

##### 1. Surface Roughness Trends:

- Cutting speed inversely affects surface roughness; higher speeds result in smoother surfaces due to reduced cutting forces and vibrations (Chakraborty & Ghosh, 2019).
- Higher feed rates increase surface roughness due to larger chip thickness and increased cutting forces (Srinivasan & Lee, 2004).

##### 2. Optimal Machining Conditions:

- Optimal cutting speeds (e.g., 400 m/min) produce smoother surfaces, even with higher

feed rates, emphasizing the need to adjust speed for better surface quality.

3. Environmental Considerations:
  - Higher cutting speeds improve surface quality but slightly increase energy consumption. Optimizing cutting parameters can reduce both energy use and waste generation, contributing to more sustainable practices (Sundararajan & Xie, 2017).
  - Minimizing tool wear through optimization also reduces waste and energy consumption associated with frequent tool replacements (Kujawski & Rukavina, 2019).

### 5.2 Practical Implications

The findings offer significant practical insights for industries requiring precision and efficiency:

1. Optimizing CNC Milling Operations:
  - Manufacturers can reduce surface roughness and energy consumption by adjusting cutting speed and feed rate, especially in high-volume production where both quality and cost are critical.
2. Energy Efficiency:
  - Optimizing CNC milling processes can lower energy consumption, reduce carbon emissions, and contribute to sustainability goals.
3. Tool Life and Cost Reduction:
  - By minimizing tool wear, manufacturers can extend tool life, reducing replacement costs and environmental waste.
4. Material Waste Reduction:
  - Optimizing machining parameters also helps reduce material waste, especially important in industries with high material costs.

### 5.3 Recommendations for Future Research

Several areas for further exploration are recommended:

1. Effect of Tool Geometry:
  - Future studies should investigate the impact of tool geometry (e.g., rake angle, cutting edge radius) on surface finish and tool wear.
2. Advanced Tool Coatings:
  - Exploring the role of coatings like TiN or TiAlN could help improve tool durability and surface finish while reducing the environmental impact.
3. Additional Factors:
  - Future research could include factors like depth of cut, cutting fluid type, and machine tool

conditions to better understand their influence on machining outcomes.

4. Integration of Machine Learning:
  - Real-time optimization using machine learning algorithms could continuously adjust parameters, improving surface roughness, energy consumption, and tool life.
5. Long-Term Sustainability Studies:
  - Long-term studies assessing the cumulative environmental impact, including energy consumption and waste generation, could provide valuable insights into the sustainability of CNC milling.

## VI. CONCLUSION

This study underscores the importance of optimizing CNC milling parameters to improve surface quality and minimize environmental impact. By adjusting cutting speed and feed rate, manufacturers can achieve superior surface finishes while reducing energy use and waste. Future research should focus on tool geometry, coatings, and machine learning to further refine optimization strategies, helping meet the growing demand for high-quality products produced sustainably.

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