

Effect of Machining Parameters on Surface Roughness during Milling of Steel

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ABSTRACT

Surface roughness has been the most extensively studied parameter in machining and remains a key indicator of process efficiency, surface quality, energy consumption, and productivity. With the growing emphasis on sustainable manufacturing, this study investigates the effect of a biodegradable lubricant (sunflower oil) on surface roughness during milling, as an alternative to conventional synthetic cutting fluids. An experimental analysis was conducted on SS 304, a widely used yet difficult-to-machine engineering material, using the Response Surface Methodology with a Central Composite Design. A total of 45 experiments were conducted by varying the depth of cut, feed per tooth, cutting speed, and cutting conditions (sunflower oil, conventional lubricant, and dry machining). The results were analyzed using ANOVA, which revealed depth of cut as the most significant factor influencing surface roughness with a contribution of 58.49%, followed by cutting speed (7.53%) and feed per tooth (5.89%), while cutting condition showed the least significance. Although the improvement in surface quality with sunflower oil was marginal compared to that with the conventional lubricant, it was notably superior to dry machining, demonstrating that sunflower oil can be effectively used as a sustainable lubricant without compromising surface quality.

Keywords: Surface Roughness, ANOVA, Milling Machine.

1. INTRODUCTION

Traditional cutting fluids are predominantly formulated using mineral oils derived from petroleum by-products [1]. However, mineral oil-based cutting fluids exhibit poor biodegradability and generate significant carbon emissions and greenhouse gases during production and use, raising serious environmental concerns. In addition, they contain irritating volatile organic compounds (VOCs), which pose potential risks to the working environment and operator health. These environmental, health, and regulatory challenges have prompted manufacturers to explore sustainable alternatives to conventional cutting fluids [2].

Among the proposed solutions, dry machining has attracted considerable attention due to its environmental and economic benefits [3], [4]. Dry cutting has been reported to reduce manufacturing costs by approximately 7–17% compared to machining processes that employ conventional coolants [5]. Furthermore, dry machining eliminates the negative environmental impacts associated with the use, handling, and disposal of cutting fluids. Despite these advantages, dry machining is not universally applicable, particularly when machining hard-to-cut materials [6], [7], [8]. The absence of cooling and lubrication often results in excessive tool wear, elevated cutting temperatures, degraded surface quality, and reduced dimensional accuracy,

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which ultimately limit productivity and process reliability [9], [10].

Consequently, the use of cutting fluids remains essential in many machining operations to ensure acceptable performance and product quality. Proper application of cutting fluids improves tool life, reduces power consumption, enhances dimensional accuracy, and significantly improves surface roughness [6], [11], [12]. Additionally, cutting fluids protect machined surfaces from environmental degradation and corrosion [13], [14]. However, the economic burden associated with cutting fluids, including procurement, maintenance, disposal, and health-related costs, must be carefully evaluated against their performance benefits. Several researchers have highlighted this trade-off, emphasizing that while flood cooling outperforms dry cutting in terms of machining performance, it introduces economic, environmental, and occupational health concerns that cannot be ignored.

In response to these challenges, plant-based cutting fluids have emerged as promising environmentally benign alternatives to conventional mineral oil-based lubricants [15]. Plant oils, derived from renewable natural sources, are characterized by low volatility, high lubricity, and excellent biodegradability [16], [17], [18]. These oils readily decompose in natural environments, making them environmentally sustainable options. From a tribological standpoint, the effectiveness of plant oils is attributed to their fatty acid composition. Unsaturated fatty acids (UFAs) enhance fluidity and lubricity, while saturated fatty acids (SFAs) contribute to the formation of dense and stable lubricating films. This protective oil film prevents direct metal-to-metal contact at the tool-workpiece interface, thereby reducing friction and wear, extending tool life, and improving overall machining performance [19]. As a result, plant-based oils are increasingly being investigated as viable cutting fluids that address both environmental sustainability and machining efficiency [20], [21], [22].

Parallel to the development of sustainable lubricants, researchers have extensively applied process optimization techniques to improve machining performance [23], [24], [25]. By considering multiple input parameters such as cutting speed, feed rate, and depth of cut, numerous studies have successfully optimized output responses including surface roughness [26], tool wear [27], and specific cutting energy [28], [29] for various workpiece materials. For instance, Agrawal C. et al. optimized tool wear, specific energy cutting, and surface roughness during the machining of Ti-6Al-4V under different cutting environments [30]. Similarly, Sajid Raza et al. investigated the influence of cutting parameters on surface roughness, burr formation, and energy consumption during the macro-milling of Aluminum 6061-T6 [31], [32]. These studies underline the importance of simultaneously optimizing cutting conditions and machining parameters to achieve improved productivity, surface quality, and economic efficiency.

Despite these advancements, a clear research gap remains. While several studies have examined biodegradable lubricants and parameter optimization independently, limited work has systematically evaluated the performance of specific plant-based oils under controlled experimental designs and directly compared them with conventional lubricants and dry machining conditions for difficult-to-machine materials. In particular, the milling of austenitic stainless steel SS 304, known for its high work-hardening tendency and poor machinability, has received limited attention in the context of biodegradable lubricants. Therefore, a comprehensive investigation combining sustainable lubrication strategies with statistical optimization is required to assess their true potential. The present study addresses this gap by evaluating the effectiveness of sunflower oil as a biodegradable lubricant during the milling of SS 304, using Response Surface Methodology to quantify the influence of machining parameters and cutting conditions on surface roughness.

2. MATERIAL AND METHODS

The work piece used for this study was steel alloy SS 304 due to its vast applications in various engineering applications like automobile, food and construction industry [33]. The mechanical properties of Steel, along with those of other metals used in engineering applications, are shown in Table 1.

Among the materials compared, SS304 exhibits the highest density and relatively high hardness. More importantly, it offers a superior combination of mechanical properties, including good strength, excellent ductility, and high toughness, along with outstanding corrosion resistance. Compared to aluminum alloys and carbon or martensitic stainless steels, SS304 provides more stable and reliable mechanical performance, which justifies its selection for this study. In addition to this, the chemical composition of SS 304 is shown in Table 2.

Table 1: Mechanical Properties of some commonly used materials [33], [34], [35], [36], [37].

Properties	SS304	Al 6061-T6	Al7075- T6	SAE/AISI 1117	AISI4140*	SS 416 (Annealed)
Density (g/cm ³)	7.93	2.7	2.81	7.87	7.85	7.75
Hardness (HB/HRB/ HRC)	123–160 HB	95 (HB)	~ 7 (eq.) HRC	121~137 (HB)	197 (HB)	262 (HB)
Ultimate Tensile Strength (MPa)	515 – 620	310	572	430 ~ 480	1590	517
Yield Strength (MPa)	205 – 250	275	503	230 ~400	1460	276
Modulus of elasticity (GPa)	193	69	71.7	200	207	200
Ductility (%)	55-60	12 – 14	11	15~23	12.5	30

Table 2: Chemical properties of Stainless Steel 304 [33], [38].

Contents	%
Fe	Balance
Cr	17.5–19
Ni	8.0–10.5
C	≤ 0.08
Si	≤ 1.00
P	≤ 0.04
S	≤ 0.03

For the selection of machining variables, feed per tooth, depth of cut, and cutting speed were varied, as these are the most variable machining parameters on any shop floor. In addition to this, to investigate the effect of a sustainable lubricant on surface finish, sunflower oil was used, along with conventional cutting fluid and dry machining conditions, to conduct a comparative analysis to investigate the effect of lubricant on surface roughness under varying machining parameters.

A Sandvik end mill cutter with a 25 mm diameter was used in this experimental investigation on an MV-1060 YDPM milling machine. A TIME® 3110 roughness tester was used to measure the surface roughness (μm). The milling operation was carried out on an MV-1060YDPM milling machine, using a 25mm diameter end milling cutter. Each machining condition was repeated twice to ensure consistency, and the slots were carefully cleaned with compressed air and then treated with alcohol, as shown in Figure 1. In our study, we employed two cutting tools with a diameter of 25 mm each. The first tool, R390-025B25-11L, was equipped to accommodate two inserts, spaced 180 degrees apart. The insert R390-025B25-11L is shown in Figure 2. Table 3 presents the details of the specifications insert.

Table 3: Tool Holder, End mill cutter and inserts specifications.

Specifications	Descriptions
Tool holder	WALTER A170M.063.080.25
End mill cutter	R390-0.25B25-11M & R390-028B25-11L
Insert	R390-11 T3 02E-KM H13A
Tool diameter	25mm
Maximum cutting velocity (m/min) of the insert	1000
Feed per tooth (mm/tooth)	0.08-0.18



Figure 1: MV-1060YDPM milling machine.



Figure 2: Cutting tool having a diameter of 25mm.

Target Circool 32, as recommended by the machine manufacturer, was employed as the reference coolant to evaluate machining responses under different cutting conditions. The properties of this conventional cutting fluid, along with those of the selected sustainable alternatives, are presented

in Table 4. In addition, sunflower oil was used as a cutting fluid to draw a direct comparison of machining performance and to derive conclusions regarding its effectiveness. Furthermore, canola oil, widely reported in the literature as a sustainable cutting fluid, was included for comparison, and its properties are summarized in Table 4. The chemical properties of conventional cutting oil are shown in Table 5.

Table 4: Physical Properties of Conventional & Sustainable Oils.

Properties	Target Circool 32 [33]	SunFlower Oil [33-34]	Canola Oil[35]
Density (25 °C)	0.87 g/cm ³	0.9188 g/cm ³	0.92g/cm ³
Flash Point	200°C	324–342 °C	275 - 290°C
Viscosity (35 °C)	2.7×10^{-5} MPa·s	41.11 mPa·s	78.2 Mpa.s
Melting Point/Pour Point	-6°C	-17 to -20 °C	-12 to -15 °C
Price Per Liter	600-650 pkr	500-600 pkr	500-600 pkr

Table 5: Chemical Properties of Conventional Cutting Oil.

Properties	Value
Kinematic Viscosity @100°C, cSt ASTM D445	5.3
Kinematic Viscosity @40°C, cSt ASTM D44	31.5
Viscosity Index ASTM D2270	99
Flash Point (COC), °C ASTM D92	200
Pour Point, °C ASTM D97	-6

It is important to distinguish the “flooded condition” from the Minimum Quantity Fluid (MQF) technique. While sunflower oil has been investigated for MQF applications, which involve minimal fluid flow rates (e.g., 50 mL/h, often in aerosol form) primarily focused on reducing friction and minimizing material adhesion at the tool-chip interface, “flooded” implies a substantially higher volume application. Sunflower oil presents itself as a promising “eco-friendly” and “environmentally friendly alternative” to conventional cutting fluids, directly addressing growing environmental challenges and human health concerns associated with traditional petroleum-based coolants. Its adoption contributes positively to environmental sustainability by reducing water pollution from machining processes and lessening dependence on non-renewable oil resources, thereby supporting “clean water and oceans” initiatives. The properties of Sunflower Oil are presented in Table 4, along with a comparison between Conventional and Biodegradable oil.

For the design of experiments, various DOE techniques are widely used for similar investigations like Taguchi L9 array, full factorial, fractional factorial design and response surface method. Response Surface Methodology (RSM) was employed for the design of experiments (DOE), and 45 experimental runs were conducted to systematically investigate the effects of machining parameters on the selected response variables. RSM offers the advantage of achieving accurate modeling and optimization with significantly fewer experiments compared to conventional full factorial techniques, making it a widely adopted approach in machining studies. Depth of cut and Feed per Tooth were the machining parameters varied at 3 levels, as shown in Table 6.

Table 6: Machining parameters and their levels.

Depth of cut (mm)	Cutting Speed (m/min)	Feed per Tooth (mm/tooth)	Cutting Condition	Number of inserts
0.5	30	0.08	Dry	2
1.25	80	0.13	Conventional	2
2.0	130	0.18	Sustainable	2

3. RESULTS AND DISCUSSION

This chapter discusses the experimental results for surface roughness and energy consumption obtained from the designed experiments. Following the Box–Behnken response surface methodology (RSM) design, surface roughness and specific cutting energy were measured and analyzed using main effect plots and analysis of variance (ANOVA). Improving surface quality while reducing energy consumption is critical for modern manufacturing due to increasing production demands and environmental concerns. Milling, being a widely used machining process, was therefore selected to evaluate the influence of machining parameters on these performance indicators.

The results indicate that depth of cut is the most influential parameter, contributing 58.49% to surface roughness and 38.79% to specific cutting energy in down milling, while cutting speed accounts for 25.29% of the variation in specific cutting energy. Confirmatory experiments conducted under extreme conditions validated the reliability of the developed models.

3.1 Effect of Machining Parameters on Surface Roughness

The main-effect plots and ANOVA results reveal that surface roughness increases with increasing cutting speed and feed per tooth, as shown in Figure 3. In contrast, it decreases with increasing depth of cut. Higher feed rates generate larger chip volumes, which adversely affect surface quality. Increased cutting speed raises the cutting temperature, promoting built-up edge (BUE) formation on the tool due to SS304's adhesive nature, thereby increasing surface roughness. Additionally, elevated cutting forces and vibration amplitudes at higher cutting speeds further contribute to surface degradation.

ANOVA results confirm that depth of cut is the only statistically significant parameter affecting surface roughness, contributing 58.49% of the total variation, while cutting speed and feed per tooth were found to be statistically insignificant ($P > 0.05$).

An ANOVA was conducted to assess the impact of various input parameters on surface roughness, with the results presented in Table 7. It was determined that the depth of cut is a significant factor, accounting for 58.49% of the overall results. In contrast, cutting speed, along with the other parameters, was considered insignificant, as they all had P values exceeding 0.05.

Surface Plots present a three-dimensional view of the model (Figure 4). The following shows the combined effect of a set of variables on surface roughness in each plot. The plots are discussed accordingly. Figure 4 presents the surface plots showing the combined influence of machining parameters on surface roughness (Ra). It can be observed that both feed per tooth and feed rate exert the most significant effect, with higher values leading to a considerable increase in surface roughness and thereby deteriorating surface quality. Depth of cut also contributes to increased roughness, though its effect is less pronounced than that to feed parameters. On the other hand, cutting speed shows an improving influence, as higher cutting speeds generally result in a smoother surface finish; however, this effect is not sufficient to completely offset the adverse impact of higher feed per tooth or feed rate. Overall, the results indicate that minimizing feed

parameters and depth of cut, while maintaining higher cutting speeds, is favorable for achieving improved surface finish. Therefore, an appropriate optimization of machining parameters is essential to balance productivity with surface quality in the manufacturing process.

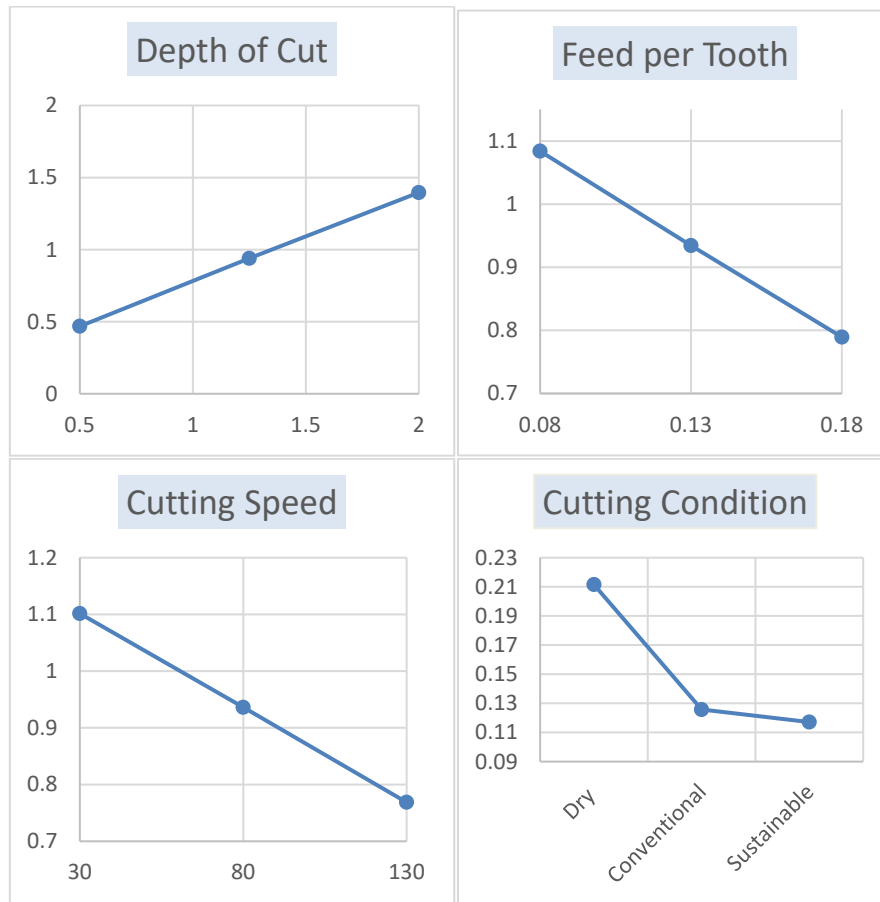


Figure 3: Main Effect Plots for Average Surface Roughness.

Table 7: ANOVA results for this study.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Depth of Cut	2	10.3339	58.49%	10.333	5.16693	91.72	0.000
Feed per Tooth	2	1.0414	5.89%	1.0414	0.52070	9.24	0.000
Cutting Speed	2	1.3298	7.53%	1.3298	0.66488	11.80	0.000
Cutting Condition	2	0.4007	2.27%	0.4007	0.20037	3.56	0.033
Error	81	4.5631	25.83%	4.5631	0.05633	-	-
Lack-of-Fit	30	4.5305	25.64%	4.5305	0.15102	236.63	0.000
Pure Error	51	0.0325	0.18%	0.0325	0.00064	-	-
Total	89	17.6688	100.00%	-	-	-	-

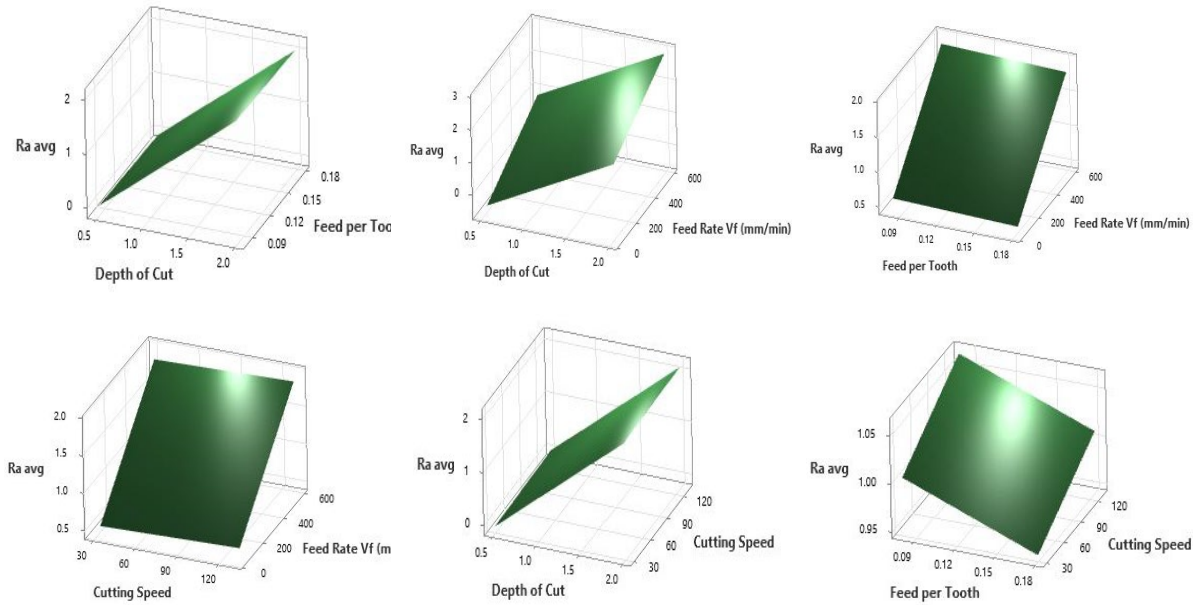


Figure 4: Surface plots for Surface Roughness.

3.2 Validation of result

In this experimental study, the effects of sustainable lubricants on surface roughness and energy consumption during the milling of stainless steel 304 are investigated. Key machining parameters have been identified, and an analysis of variance was conducted to assess their impacts. This analysis has revealed the most and least effective machining conditions, detailed in Table 8.

Table 8: Machining parameters and their levels.

Responses		Cutting Speed (m/min)	Feed Per Tooth (mm/tooth)	Depth of cut (mm)	Cutting Condition	Results
Surface Roughness (µm)	Best	0.18	130	0.5	Sustainable	0.16745
Surface Roughness (µm)	Average	0.13	80	1.25	Conventional	0.95739
Surface Roughness (µm)	Worst	0.08	30	2	Dry	2.13674

To ensure that our findings were reliable, we carried out experimental validations by milling using the best and worst combinations of input parameters for each of the output responses we measured. The outcomes of these experiments, summarized in Table 8, reaffirm the validity of our experimental design and provide a solid foundation for understanding the influence of sustainable lubricants in this context. By examining the interplay among these factors, we aim to provide valuable insights into more eco-friendly machining practices, ultimately promoting sustainable manufacturing while maintaining efficiency and quality.

4. CONCLUSION

Overall, the experimental results demonstrated that depth of cut is the dominant machining parameter governing surface roughness during SS304 milling, outweighing the effects of feed per tooth and cutting speed.

- Statistical analysis using main effect plots and ANOVA confirmed that feed per tooth, cutting speed, and depth of cut significantly influence surface roughness, validating the adequacy of the experimental design.
- Among these parameters, depth of cut (a_p) was the most influential, contributing 58.49% of the total variation in average surface roughness.
- The results show that surface roughness increases with increasing feed per tooth and cutting speed, whereas it decreases with increasing depth of cut within the investigated range.
- Interaction trends observed in the response surface plots further support that depth of cut plays a stabilizing role in improving surface finish under the selected cutting conditions.

Practical implication: To achieve a better surface finish when milling SS304, operators should prioritize using a higher depth of cut within the tested range, combined with lower feed per tooth and cutting speed, as depth of cut was identified as the dominant influencing factor.

Future work

- The performance of various sustainable lubricants should be systematically evaluated and compared with conventional synthetic cutting fluids to assess their effectiveness in improving surface quality.
- A detailed investigation of the service life and degradation behavior of sustainable lubricants, compared with conventional lubricants, is recommended to assess their long-term feasibility in industrial machining.
- Future optimization studies should incorporate additional performance indicators, such as burr formation, tool life, material properties, and machining cost, to develop a more comprehensive, industry-relevant optimization framework.
- Machine learning models should be developed and trained using experimental data to accurately predict surface roughness (R_a), enabling faster decision-making and intelligent process planning.

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