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Effect of Cutting Parameters on Surface Roughness in CNC Milling Process

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Abstract: Surface roughness is a critical quality indicator in the CNC milling process, directly influencing the functional performance, fatigue life, and aesthetic quality of machined components. The rapid development of advanced materials and high-precision manufacturing has intensified the need to understand and optimize machining parameters to achieve superior surface integrity. This study aims to systematically analyze the effects of cutting parameters on surface roughness in CNC milling by synthesizing and critically discussing findings from recent experimental and analytical studies. A comprehensive literature-based research method was employed, involving peer-reviewed journal articles indexed internationally and nationally, focusing on milling operations across metallic, composite, polymeric, and wood-based materials. The analysis reveals that feed rate consistently emerges as the most influential parameter affecting surface roughness, followed by cutting speed and depth of cut, although their relative significance varies depending on material properties, tool geometry, lubrication conditions, and machining strategies. Advanced approaches such as Taguchi methods, response surface methodology, and machine learning-based models demonstrate substantial potential in predicting and minimizing surface roughness. The findings confirm that optimal selection and control of cutting parameters can significantly enhance surface quality and machining efficiency. This article contributes a consolidated scientific perspective that can serve as a reference for researchers and practitioners in optimizing CNC milling processes.

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INTRODUCTION

Computer Numerical Control (CNC) milling is one of the most widely applied machining technologies in modern manufacturing industries due to its high precision, operational flexibility, and capability to produce complex geometries with consistent quality. CNC milling is extensively used in automotive, aerospace, medical device, mold and die, and precision engineering industries. As manufacturing systems increasingly emphasize product quality, productivity, and process efficiency, attention to machining output characteristics, particularly surface quality, has become a critical aspect of CNC-based production.

Surface roughness is a key indicator of surface quality that characterizes the topographical condition of a machined surface. It directly affects the functional performance of components, including wear resistance, frictional behavior, dimensional accuracy, fatigue strength, and aesthetic appearance. Excessive surface roughness can accelerate crack initiation, increase stress concentration, and reduce component reliability during service. Consequently, controlling surface roughness is not merely a matter of visual quality but a fundamental requirement for ensuring mechanical integrity and long-term performance of machined parts.

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In CNC milling operations, surface roughness is governed by a complex interaction between cutting parameters, workpiece material properties, tool geometry and condition, and machining environment. Among these factors, cutting parameters such as feed rate, cutting speed, and depth of cut have consistently been identified as the most influential variables affecting surface roughness. Improper selection of these parameters can lead to increased cutting forces, vibration, unstable chip formation, and built-up edge, all of which adversely affect surface integrity.

Numerous experimental studies have investigated the influence of cutting parameters on surface roughness using statistical design and optimization techniques. Approaches such as the Taguchi method and analysis of variance have been widely employed to quantify the contribution of each parameter. These studies generally report that feed rate has the highest contribution to surface roughness variation, followed by cutting speed and depth of cut. This trend has been observed across different materials and machining conditions, indicating the dominant role of feed rate in determining surface quality in milling processes.

The sensitivity of surface roughness to cutting parameters, however, is strongly dependent on the characteristics of the workpiece material. In the milling of aluminum alloys, feed rate remains the most significant factor, while cutting speed plays an important role in stabilizing chip formation and reducing built-up edge. Several studies on aluminum alloys have shown that increasing cutting speed within an optimal range can significantly improve surface finish. In contrast, for harder materials such as stainless steels and tool steels, depth of cut and tool geometry also exert a considerable influence due to their direct impact on cutting forces and dynamic stability.

Beyond metallic materials, CNC milling is increasingly applied to non-metallic materials such as polymers, composites, and wood-based products. Machining of these materials presents additional challenges due to anisotropy, heterogeneous structure, and distinct thermo-mechanical behavior. Studies on wood milling have demonstrated that fiber orientation and material structure can significantly influence surface roughness, in some cases exceeding the effect of certain cutting parameters. Similarly, research on polymeric and composite materials has consistently indicated that lower feed rates and smaller depths of cut are essential for achieving acceptable surface quality.

Recent advances in manufacturing research have promoted the use of advanced modeling and optimization techniques to predict and control surface roughness. In addition to conventional statistical methods, multivariate modeling and machine learning-based approaches have shown high predictive accuracy in capturing the nonlinear relationships between cutting parameters and surface roughness. These techniques offer advantages in handling complex interactions and process variability that are difficult to represent using purely empirical models.

Despite the extensive body of research on surface roughness in CNC milling, reported results often vary in terms of parameter significance and optimal conditions. Differences in material type, experimental setup, machining strategy, and analytical approach contribute to inconsistent conclusions across studies. As a result, it remains challenging to derive generalized guidelines for parameter selection that are applicable across different machining scenarios. This situation highlights the need for a comprehensive and critical synthesis of existing research to identify consistent trends and key influencing factors.

Most previous studies have focused on specific materials or optimization techniques in isolation, limiting the availability of integrated insights across material categories and analytical methods. Furthermore, the rapid development of advanced predictive techniques has not yet been

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comprehensively synthesized in relation to conventional experimental findings. Addressing this gap is essential for improving both academic understanding and industrial application of surface roughness control in CNC milling.

Based on these considerations, this study aims to systematically analyze the effects of cutting parameters on surface roughness in CNC milling through a comprehensive review and critical discussion of recent research findings. The analysis encompasses a wide range of materials, including metallic and non-metallic workpieces, as well as various experimental and optimization approaches. By synthesizing dispersed findings, this study seeks to identify dominant parameters, consistent trends, and methodological implications.

The primary contribution of this article lies in providing an integrated scientific perspective on the influence of cutting parameters on surface roughness in CNC milling. The synthesized insights are expected to serve as a reliable reference for researchers in designing future studies and for industrial practitioners in selecting effective machining strategies. Ultimately, this work supports efforts to enhance product quality, process efficiency, and reliability in CNC milling operations.

RESEARCH METHOD

Research Design

This study employs a qualitative and analytical literature review design to investigate the effects of cutting parameters on surface roughness in CNC milling processes. The literature review approach was selected to enable a systematic synthesis of empirical findings from previous experimental and analytical studies without conducting new experiments. This design is appropriate for identifying dominant parameters, consistent trends, and methodological patterns reported across different materials and machining conditions.

Data Sources and Search Strategy

Relevant scientific publications were collected from reputable national and international databases that index peer-reviewed journals and conference proceedings. The search focused on publications released between 2015 and 2025 to ensure the inclusion of recent and methodologically relevant studies. Keywords used in the search process included combinations of “CNC milling,” “surface roughness,” “cutting parameters,” “feed rate,” “cutting speed,” “depth of cut,” and “machining optimization.” Only articles written in English and published in recognized scientific outlets were considered.

Inclusion and Exclusion Criteria

The selection of literature was guided by predefined inclusion and exclusion criteria to ensure relevance and consistency. Studies were included if they met the following conditions: (1) the study focused on CNC milling operations, (2) surface roughness was reported as a primary or secondary response variable, (3) cutting parameters such as feed rate, cutting speed, and depth of cut were explicitly analyzed, and (4) the study presented experimental results, statistical analysis, or validated predictive models. Studies were excluded if they focused on machining processes other than milling, did not report measurable surface roughness outcomes, or lacked sufficient methodological clarity.

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Material Scope and Machining Conditions

The reviewed studies covered a wide range of workpiece materials to provide a comprehensive perspective. These materials included metallic materials such as aluminum alloys, stainless steels, tool steels, and copper, as well as non-metallic materials including polymers, composite laminates, and wood-based materials. Both dry and lubricated machining conditions were considered, reflecting common industrial practices. Differences in tool materials, tool geometry, and machine configurations were documented where reported, but no attempt was made to standardize these variables, as the objective was to synthesize trends rather than perform direct numerical comparison.

Data Extraction and Classification

From each selected study, relevant information was systematically extracted and organized. The extracted data included material type, cutting parameters investigated, experimental design or modeling approach, measurement method for surface roughness, and key findings related to parameter significance. Surface roughness indicators such as arithmetic average roughness were considered where reported. The studies were then classified based on material category, dominant cutting parameter, and optimization or analysis technique employed.

Analytical Approach

A comparative analytical approach was used to evaluate the influence of cutting parameters on surface roughness across different studies. Emphasis was placed on identifying consistent findings regarding parameter dominance and interaction effects. Rather than aggregating numerical values, the analysis focused on qualitative trends and relative significance reported by the authors. Optimization techniques such as the Taguchi method, response surface methodology, and machine learning-based models were analyzed in terms of their reported effectiveness in predicting or minimizing surface roughness.

Reliability and Validity Considerations

To enhance the reliability of the synthesis, only peer-reviewed publications with clearly described experimental or analytical procedures were included. Cross-comparison among studies using similar materials or methods was conducted to verify consistency of reported trends. Any discrepancies in findings were interpreted in relation to differences in material properties, machining conditions, or analytical techniques, rather than treated as methodological errors.

Ethical and Reporting Considerations

This study is based entirely on previously published literature and does not involve human participants, animal subjects, or proprietary industrial data. All sources cited in the analysis are properly acknowledged in the reference list. The methodological description is presented transparently to ensure replicability of the literature selection and analysis process.

RESULTS AND DISCUSSION

Influence of Cutting Parameters on Surface Roughness

The synthesis of reviewed studies clearly indicates that cutting parameters have a significant and measurable influence on surface roughness in CNC milling processes. Across a wide range of materials and machining conditions, feed rate consistently emerges as the most dominant parameter affecting

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surface roughness, followed by cutting speed and depth of cut. This trend is repeatedly reported in experimental investigations involving metallic and non-metallic materials.

An increase in feed rate generally leads to higher surface roughness due to the increased chip load per tooth and intensified tool–workpiece interaction. Higher feed rates reduce the number of tool passes over a given surface area, resulting in more pronounced feed marks and irregular surface profiles. This behavior is consistently observed in milling operations involving aluminum alloys, steels, and copper under both dry and lubricated conditions (Okokpujie & Okonkwo, 2015; Lai et al., 2023; George et al., 2024).

Cutting speed shows a more complex relationship with surface roughness. Many studies report that increasing cutting speed within an optimal range improves surface finish by stabilizing chip formation and reducing built-up edge formation on the cutting tool (Thanasuptawee et al., 2018; Kaisan & Rusiyanto, 2020). However, excessively high cutting speeds may induce thermal effects and dynamic instability, which can deteriorate surface quality, particularly in materials sensitive to heat generation (Lai et al., 2024).

Depth of cut generally exhibits a moderate influence on surface roughness compared to feed rate. Its effect is strongly material dependent. In harder materials such as stainless steel and tool steel, higher depths of cut increase cutting forces and vibration amplitude, leading to rougher surfaces (Lubis et al., 2023; Avcı et al., 2024). In softer materials, its influence is often secondary and becomes significant mainly when combined with high feed rates.

Empirical Evidence Across Different Materials

Table 1 summarizes selected empirical findings from representative studies reviewed in this research. The table highlights material type, dominant cutting parameter, and the reported effect on surface roughness.

Table 1. Summary of empirical findings on cutting parameters and surface roughness in CNC milling

Material Type	Dominant Parameter	Observed Effect on Surface Roughness	Reference
Aluminum alloys (AA6061, AA2024)	Feed rate	Significant increase in roughness with higher feed rate	Ribeiro et al. (2017); Hoang (2023)
Stainless steel	Feed rate, depth of cut	Increased roughness due to higher cutting forces	Lubis et al. (2023)
Tool steel	Feed rate	Primary contributor to roughness variation	Avcı et al. (2024)
Copper	Feed rate	Strong correlation with surface irregularities	Okokpujie & Okonkwo (2015)
Wood-based materials	Feed rate, grain orientation	Roughness influenced by feed rate and anisotropy	Ibrisevic et al. (2023)
PMMA and composites	Feed rate, depth of cut	Lower values improve surface quality	Susac & Frumuşanu (2022); Nurhaniza et al. (2016)

The table confirms that despite differences in material properties and machining environments, feed rate remains the most consistently dominant parameter influencing surface roughness. This consistency supports the generalizability of feed rate control as a primary strategy for surface quality improvement.

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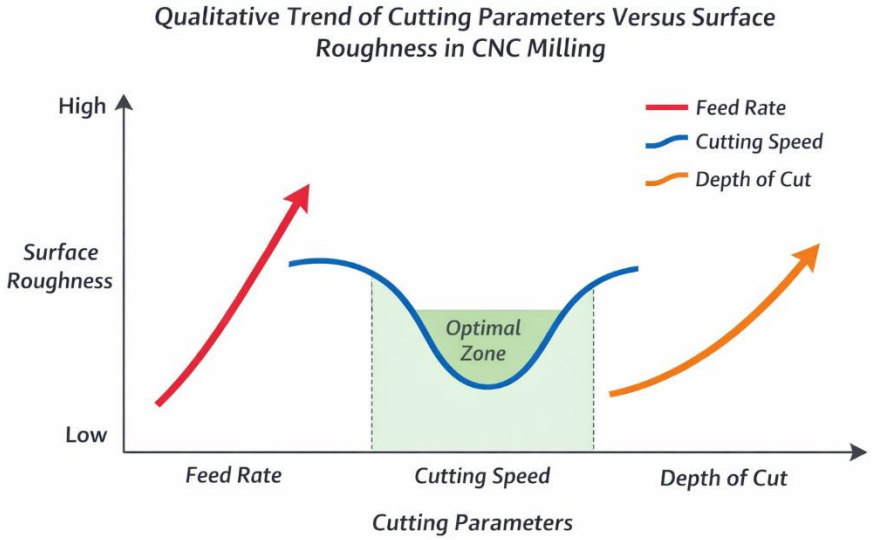
Comparative Trend Visualization

Based on the empirical trends reported across studies, Figure 1 illustrates the qualitative relationship between cutting parameters and surface roughness in CNC milling. The diagram synthesizes reported trends rather than numerical data.

Figure 1. Qualitative trend of cutting parameters versus surface roughness in CNC milling



This visualization highlights the non-linear and interaction-driven nature of surface roughness formation, reinforcing the need for multi-parameter optimization rather than single-factor adjustment.

Effectiveness of Optimization and Modeling Approaches

Several reviewed studies employ optimization techniques to identify parameter combinations that minimize surface roughness. Taguchi-based designs and response surface methodology are widely reported as effective tools for reducing experimental effort while identifying significant parameters and optimal levels (Ribeiro et al., 2017; Hoang, 2023). These methods are particularly effective for systems with limited interaction complexity.

More recent studies demonstrate that machine learning-based models outperform traditional statistical approaches in predicting surface roughness, especially under complex machining conditions. Models such as artificial neural networks and hybrid learning frameworks exhibit higher prediction accuracy by capturing nonlinear relationships between cutting parameters and surface responses (Bajić et al., 2024; Çevik & Sarıışık, 2025). These approaches are especially advantageous for multi-material and multi-condition environments where empirical modeling becomes less reliable.

Discussion of Consistency and Variability in Findings

Although feed rate consistently emerges as the most influential parameter, variability in reported parameter significance is evident across studies. This variability can be attributed to differences in material hardness, tool geometry, cutting environment, and experimental design. For instance, depth

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of cut plays a more pronounced role in hard-to-machine materials, whereas cutting speed becomes more influential in materials prone to built-up edge formation.

These findings underscore the importance of contextual interpretation of empirical results. Rather than treating cutting parameters independently, their interaction with material properties and machining conditions must be considered to achieve reliable surface quality outcomes.

CONCLUSION

This study presents a comprehensive synthesis of recent research on the effects of cutting parameters on surface roughness in CNC milling processes. Based on the critical review of empirical and analytical studies, the findings consistently confirm that feed rate is the most dominant parameter influencing surface roughness across a wide range of materials and machining conditions. An increase in feed rate generally leads to a significant deterioration of surface quality due to higher chip load and intensified tool–workpiece interaction.

Cutting speed exhibits a non-linear influence on surface roughness. Within an optimal range, higher cutting speeds tend to improve surface finish by stabilizing chip formation and reducing built-up edge formation. However, excessively high cutting speeds may introduce thermal effects and dynamic instability, which negatively affect surface quality. Depth of cut shows a moderate and material-dependent effect, with a more pronounced influence observed in hard-to-machine materials where increased cutting forces and vibration contribute to surface irregularities.

The review also highlights the effectiveness of optimization and modeling approaches in controlling surface roughness. Conventional statistical methods such as the Taguchi method and response surface methodology remain effective for parameter optimization with limited experimental effort. More recent machine learning-based models demonstrate superior predictive capability, particularly in complex machining environments.

Overall, the results emphasize that effective control of surface roughness in CNC milling requires a holistic consideration of cutting parameters, material properties, and machining conditions. The insights provided in this study can support researchers and industrial practitioners in selecting appropriate machining strategies to improve surface quality, process efficiency, and product reliability.

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