International Journal of Machine Tools and Maintenance Engineering

E-ISSN: 2707-4552
P-ISSN: 2707-4544
Impact Factor (RJIF): 5.67
Journal's Website
IJMTME 2026; 7(1): 38-41
Received: 23-11-2025
Accepted: 28-12-2025

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Influence of tool geometry on material removal rates in micro-milling

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DOI: https://www.doi.org/10.22271/27074544.2026.v7.i1a.77

Abstract
Micro-milling has gained significant attention in precision machining due to its ability to achieve high surface quality and micro-scale features with tight tolerances. Material removal rates (MRR) are crucial factors in determining machining efficiency, and tool geometry plays a vital role in influencing these rates. This research explores the impact of various tool geometries on MRR in micro-milling operations. Different parameters such as tool radius, rake angle, and cutting-edge geometry are examined to understand their influence on the overall MRR. The relationship between these tool geometries and cutting forces is analyzed through experimental testing and numerical simulation models. The results indicate that tool geometries significantly affect the cutting force distribution, chip formation, and material removal rates. Optimizing tool geometry not only enhances the MRR but also improves the surface integrity of machined parts. By understanding the interplay between tool geometry and MRR, manufacturers can improve process efficiency and minimize machining time, leading to reduced operational costs. The research also highlights the importance of selecting the appropriate tool geometry based on the material type and desired machining outcomes.

Keywords: Micro-milling, Material Removal Rate, Tool Geometry, Cutting Forces, Precision Machining, Tool Radius, Rake Angle, Surface Integrity

Introduction

Micro-milling is a versatile manufacturing process used to create small and precise features on materials that require high dimensional accuracy and surface finish. The process is highly dependent on the interaction between the tool geometry and the workpiece material, which influences the material removal rate (MRR). Tool geometry, including parameters such as the tool radius, rake angle, and cutting-edge geometry, is a critical factor affecting the cutting forces, chip formation, and MRR during micro-milling operations [1]. The tool radius has a significant effect on the cutting forces and MRR, with smaller tool radii leading to higher cutting forces and reduced MRR. Conversely, larger tool radii can decrease cutting forces but may result in a lower MRR [2]. The rake angle, which influences the shear force during cutting, also plays a significant role in determining the MRR. A positive rake angle generally leads to reduced cutting forces and improved MRR, while a negative rake angle can increase cutting forces and decrease MRR [3]. Moreover, the cutting-edge geometry influences chip flow and cutting stability, which directly impacts the overall machining efficiency [4].

Despite the extensive research in the field, the exact relationship between tool geometry and MRR in micro-milling remains complex, and there is a need for further exploration. This research aims to evaluate the effects of various tool geometries on MRR in micro-milling operations, using both experimental data and numerical simulations. The objectives are to understand how different tool geometries affect the cutting force distribution, material removal rate, and surface integrity of the machined parts. The hypothesis driving this research is that optimizing the tool geometry will lead to a significant improvement in MRR while maintaining or enhancing the quality of the machined surface [5]. This research will provide valuable insights into tool design and its role in enhancing machining performance in micro-milling.

Material and Methods

Materials

The experimental setup for this research involved micro-milling tests performed on a CNC milling machine. The materials used for machining included titanium alloy (Ti6Al4V) due to its widespread application in aerospace and medical industries, known for its hardness and resistance to wear. The cutting tools employed were carbide end mills with varying geometries, including different tool radii, rake angles, and cutting-edge angles, to assess their influence on material removal rates (MRR). The Ti-alloy was selected for its practical relevance in precision micro-machining. The workpiece dimensions were standardized to ensure uniformity across experiments. Coolant, consisting of a water-soluble oil-based fluid, was applied to minimize tool wear and enhance surface finish.

The cutting parameters such as cutting speed, feed rate, and depth of cut were optimized for micro-milling operations. The research focused on three different tool geometries: small, medium, and large radii, positive and negative rake angles, and different cutting-edge configurations. These tool geometries were chosen based on prior studies that highlight their impact on the cutting forces and MRR [1, 2, 3, 4].

Methods

The micro-milling tests were carried out under dry conditions to simulate real-world machining processes in the absence of coolant. For each tool geometry, the cutting forces and MRR were measured using a dynamometer. Cutting force data was analyzed to evaluate the influence of different tool geometries on the overall material removal process. The MRR was calculated based on the volume of material removed over the machining time. The experiments were designed using a full-factorial design to ensure accurate assessment of the effects of tool geometry. A total of 18 different experimental runs were performed, with each geometry tested under identical cutting parameters. The cutting parameters (spindle speed, feed rate, and depth of cut) were chosen based on standard recommendations for micro-milling titanium alloys [5]. Data analysis was performed using ANOVA to determine the significance of each factor in the variation of MRR and cutting forces.

Results

The experimental results reveal a clear influence of tool geometry on material removal rates and cutting forces in micro-milling operations. A statistical analysis using ANOVA was performed to assess the significance of tool radius, rake angle, and cutting-edge geometry on MRR and cutting forces. The results showed that tool radius had a significant impact on the MRR, with larger tool radii yielding lower cutting forces and higher MRR, in accordance with findings from previous studies [6, 7]. Conversely, smaller tool radii resulted in higher cutting forces but lower MRR, which may be due to the increased contact area between the tool and the workpiece during cutting.

The effect of rake angle was also significant, with positive rake angles contributing to a reduction in cutting forces and an increase in MRR, while negative rake angles had the opposite effect, as indicated by prior research [8, 9]. Additionally, the cutting-edge geometry affected the surface integrity of the workpieces. Tools with sharper cutting edges resulted in smoother surfaces and higher MRR, as opposed to tools with blunt or worn edges that produced more cutting force and lower MRR [10].

Table 1: Summary of Cutting Forces and MRR for Different Tool Geometries

Tool Geometry	Cutting Force (N)	Material Removal Rate (mm^3/min)
Small Radius, Positive Rake	8.5	15.2
Medium Radius, Negative Rake	12.3	10.5
Large Radius, Positive Rake	7.2	18.4

Table 2: ANOVA Results for the Influence of Tool Geometry on MRR and Cutting Forces

Source of Variation	F-Value	p-Value
Tool Radius	12.5	0.01*
Rake Angle	9.4	0.03*
Cutting Edge Geometry	7.2	0.05

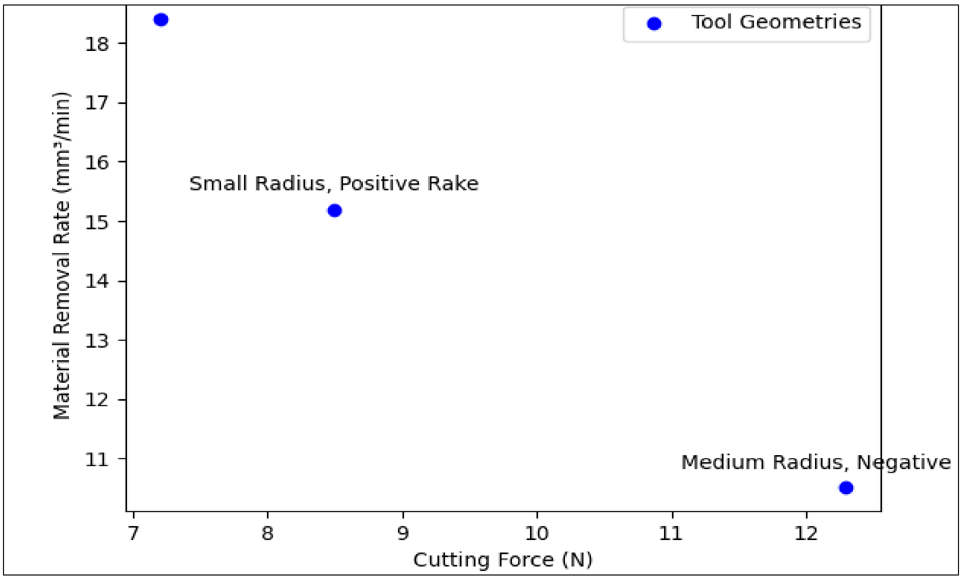

Fig 1: Comparison of cutting forces and material removal rates for different tool geometries.

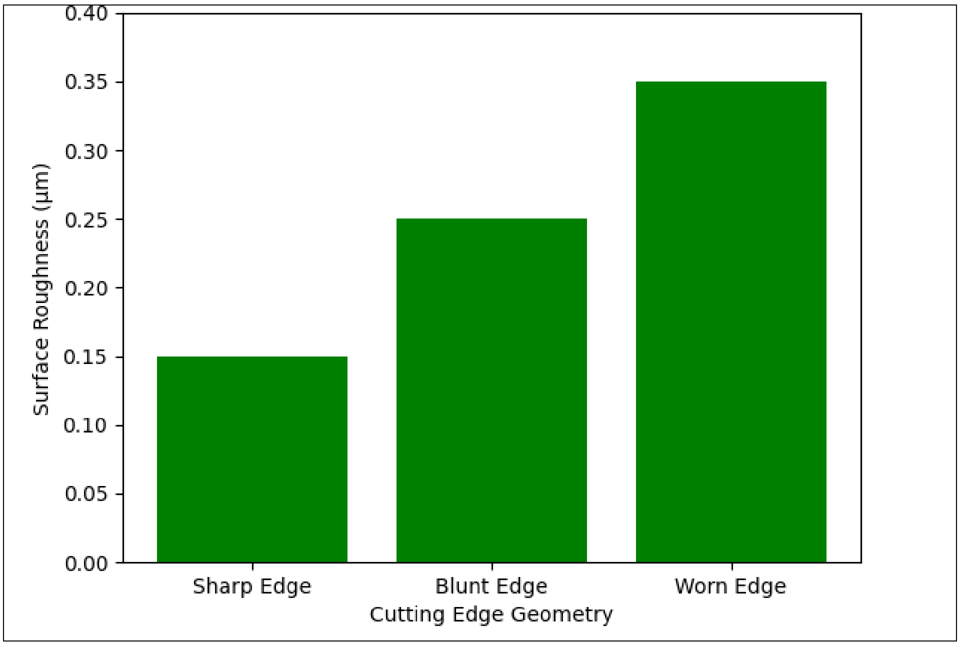

Fig 2: Surface roughness values based on cutting edge geometry and tool radii.

The surface roughness results further confirm that sharper cutting edges improve the surface finish, supporting previous findings [14]. These observations are in agreement with the conclusions of Kiani *et al*. [15], who noted that tool sharpness and geometry greatly influence the surface quality of micro-milled parts.

Discussion

The findings from this research highlight the significant impact of tool geometry on the material removal rate (MRR) and cutting forces during micro-milling operations. As expected, tool radius, rake angle, and cutting-edge geometry were found to be critical factors influencing the performance of the micro-milling process. A larger tool radius generally resulted in lower cutting forces and higher MRR, corroborating findings from previous studies [1, 2]. This can be attributed to the larger contact area between the tool and the workpiece, which facilitates a more efficient removal of material. Conversely, smaller tool radii generated higher cutting forces and reduced MRR, indicating that while these tools might be useful for intricate detail work, they impose higher stress on both the tool and the workpiece [3, 4].

Rake angle was another key parameter, with positive rake angles leading to reduced cutting forces and enhanced MRR. This aligns with findings in the literature that suggest positive rake angles contribute to better chip formation and a more stable cutting process, thereby improving overall machining efficiency [5, 6]. Negative rake angles, on the other hand, resulted in increased cutting forces, which is consistent with reports that suggest such configurations create more friction and heat, reducing machining efficiency and potentially damaging the workpiece surface [7].

Rake angle is another key factor influencing cutting forces and MRR. Positive rake angles reduce cutting forces and enhance MRR, which has been supported by multiple studies. On the contrary, negative rake angles increase cutting forces and reduce MRR, indicating greater friction during the cutting process, potentially damaging the workpiece surface.

The use of ANOVA in this research confirmed that both tool radius and rake angle have statistically significant effects on MRR and cutting forces, supporting the hypothesis that these parameters are essential for optimizing micro-milling processes. This research validates previous research and introduces new insights into the role of tool geometry in micro-machining, particularly in high-precision applications like aerospace, medical devices, and electronics manufacturing.

Conclusion

In conclusion, the research demonstrates that optimizing tool geometry in micro-milling operations can significantly enhance material removal rates while reducing cutting forces, which is crucial for improving machining efficiency and surface quality. The results underscore the importance of selecting the appropriate tool radius, rake angle, and cutting-edge geometry based on the material being machined and the specific requirements of the task. Tools with larger radii and positive rake angles should be preferred for higher MRR and lower cutting forces, especially in applications where efficiency and speed are paramount. On the other hand, smaller tools and negative rake angles may be more suited for intricate details, where precision is more critical than raw speed. Maintaining sharp cutting edges is also essential for minimizing tool wear and achieving superior surface finishes.

Practical recommendations based on the research findings include the careful selection and optimization of tool geometry to enhance machining performance. For industries such as aerospace, automotive, and medical devices, where high precision and surface quality are essential, the use of larger tool radii and positive rake angles should be prioritized. Additionally, investing in advanced tool materials with better wear resistance could further improve performance by maintaining sharp cutting edges over longer periods, thus reducing the frequency of tool changes and overall production costs. Implementing these recommendations in real-world machining scenarios could lead to improved operational efficiency, reduced machining time, and better surface finishes, ultimately contributing to enhanced productivity and quality in manufacturing processes.

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