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Comparative Evaluation of Concentric and Helical Multipass Toolpath Strategies on Surface Integrity in CATIA V5-Based Pocket Milling of Al6061

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ABSTRACT

The fabrication of aerospace components with thin-walled pocket features requires strict control of surface integrity, as surface roughness directly affects structural performance and fatigue life. However, the selection of appropriate toolpath strategies in computer-aided manufacturing (CAM) environments remains a critical challenge, particularly when multiple strategies are available for achieving similar geometric outcomes. This study investigates the influence of two roughing toolpath strategies namely Concentric-Multipass and Helical-Multipass, on surface roughness during pocket milling of Aluminum 6061 using CATIA V5. All experiments were conducted under constant machining parameters on a 3-axis CNC milling machine to ensure a consistent basis for comparison. Surface roughness (Ra) was measured using a Mitutoyo SJ-410 surface tester, while optical microscopy was employed to examine the resulting surface morphology. The analysis was performed across circular and rectangular regions to account for geometric variability. The results demonstrate that the Concentric-Multipass strategy consistently outperformed the Helical-Multipass approach in terms of surface finish. A minimum Ra value of 0.3145 µm and a maximum of 0.655 µm were recorded for Concentric-Multipass, whereas Helical-Multipass exhibited a higher peak roughness of 1.392 µm. Overall, the Concentric strategy achieved approximately 20–50% improvement in surface quality. Microscopic observations further revealed more uniform tool marks and reduced surface defects for the Concentric approach, indicating more stable cutting conditions. These findings highlight the critical role of toolpath selection in achieving high-quality surface finishes and suggest that the Concentric-Multipass strategy is more suitable for aerospace pocket milling applications requiring superior surface integrity.

Keywords: Cutting strategies; surface roughness; pocketing profiles; aerospace part

INTRODUCTION

Milling remains a critical operation in modern manufacturing due to its direct influence on productivity, dimensional accuracy, and overall product quality. Surface roughness is widely recognized as a key indicator of functional performance, as it affects wear behavior, fatigue resistance, and production cost (Reddy & Prajina 2021). In both metallic and composite materials, the selection of machining strategies, tool geometries, and cutting parameters plays a decisive role in achieving the desired surface integrity and dimensional tolerances (Nurhaniza et al. 2016). Consequently, optimizing machining strategies has become a central concern in high-precision industries such as aerospace manufacturing.

The rapid advancement of computer-aided design and manufacturing (CAD/CAM) technologies has significantly enhanced machining capabilities through improved process planning, simulation, and automated toolpath generation. CAM systems utilize geometric data from CAD models to define machining operations and optimize cutting conditions. As industrial demands continue to evolve toward higher quality, reduced lead time, and cost efficiency, the integration of advanced CAD/CAM platforms has become essential in modern manufacturing environments (Azwan et al. 2016; Kariuki et al. 2014).

Among various machining operations, pocket milling is extensively used for producing closed-boundary features in moulds, dies, and structural components. In aerospace applications, pocketed geometries are particularly important in rib and spar structures, where material removal is required to achieve lightweight designs while maintaining structural strength. However, the complexity of pocket geometries introduces significant challenges in maintaining consistent surface quality, as the resulting surface roughness is highly dependent on the selected toolpath strategy and machining conditions (Rajyalakshmi & Rao 2021).

Surface roughness is governed by a complex interaction of factors, including machining processes, workpiece material properties, and cutting conditions. It is a critical quality indicator, as it directly influences the functional performance of machined components, particularly in applications involving contact mechanics, wear resistance, fatigue behavior, and corrosion susceptibility. In high-performance industries such as aerospace, achieving low surface roughness is essential to ensure structural reliability and extended service life. Surface roughness is commonly quantified in micrometers (μm) or microinches, with lower values generally associated with improved mechanical performance and reduced failure risk.

In machining research, surface roughness is typically characterized using parameters such as the arithmetic mean roughness (Ra), maximum height (Rz), and peak-to-valley height (Ry). Among these, Ra is the most widely adopted metric due to its ability to provide a representative average of surface deviations over a defined sampling length, making it suitable for both industrial applications and comparative studies. Recent studies have reaffirmed the relevance of Ra as a reliable indicator of surface integrity, particularly in milling operations involving aerospace materials (Zhang et al. 2022; Liu et al. 2021). Furthermore, advancements in machining research have highlighted that surface roughness is highly sensitive to toolpath strategies, cutting parameters, and tool–workpiece interactions, especially in pocket milling operations where tool engagement conditions vary continuously (Wojciechowski et al. 2022; Sun et al. 2021).

Despite the availability of multiple surface characterization parameters, Ra remains the preferred choice in both academic and industrial contexts due to its simplicity, repeatability, and strong correlation with functional performance (Ding et al. 2010). Therefore, in this study, Ra was selected as the primary indicator to evaluate the surface quality of machined components under different toolpath strategies.

Although previous studies have investigated the influence of machining parameters and tool geometries on surface roughness, limited attention has been given to the comparative performance of different CAM-generated toolpath strategies, particularly within widely used industrial platforms such as CATIA V5. Existing research has predominantly focused on cutting parameters, tool wear, or general milling performance, with comparatively fewer studies systematically evaluating how specific roughing strategies affect surface integrity in pocket milling of aerospace-grade aluminum alloys. Furthermore, direct comparisons between Concentric-Multi-Pass and Helical-Multi-Pass strategies under controlled cutting conditions remain scarce, especially for Aluminum 6061 in practical aerospace pocketing applications.

Therefore, a clear research gap exists in understanding the extent to which different CATIA V5 roughing strategies influence surface roughness across varying pocket geometries. Addressing this gap is essential for improving process reliability and achieving consistent surface quality in aerospace manufacturing.

Motivated by this limitation, the present study aims to systematically investigate the effect of two commonly employed CATIA V5 toolpath strategies, namely Concentric-Multi-Pass and Helical-Multi-Pass, on the surface roughness of Aluminum 6061 during pocket milling operations. The study evaluates performance across different geometric regions under constant cutting parameters, thereby isolating the influence of toolpath strategy. The findings are expected to provide practical guidelines for selecting optimal machining strategies and contribute to enhancing surface integrity and process efficiency in aerospace component fabrication.

METHODOLOGY

CAD / CAM PREPARATION

The proposed research began with a literature review and the search for reading materials to gain some ideas and methods to be used while conducting the research. Discussions had taken place with the relevant industries to brainstorm and gather input for the best aerospace sample

part that corresponded as shown in Figure 1. to the desired requirement for the intended research. After the part was finalized, CATIAV5 was used to create modeling. All modeling processes in CATIAV5 were completed using Sketcher, Part Modeling and Assembly workbench, and Advanced Machining workbench, which allows users to create machining programming by integrating Computer-Aided Design and Computer-Aided Manufacturing (CADCAM).

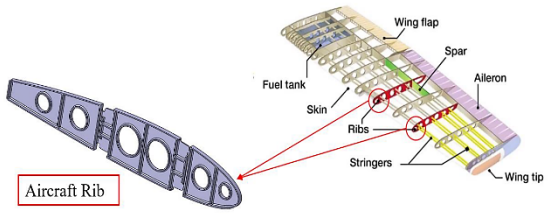


FIGURE 1. Internal structure of a wing

The project began with searching for the existing CAD part and finding the best strategies in roughing and pocketing which are helical path, and concentric path (with both multi-pass). The pocketing shapes that have been determined were circular and rectangular. For the first phase, the CAD model was modified to preserve the concept of the product for machine and model suitability.

The process continues with tool geometry, and machining parameters. Cutting parameters for all parts remains constant and includes the length of the tool reach, depth of cut, feed rate, and spindle speed. Lastly, finishing the program to proceed to the next phase after determining the machining strategies for roughing and pocketing.

To preserve the Intellectual Property (IP) of the actual part, a modification process was required. Cutting off the best portion to study was the first step, followed by scaling, stock preparation, axis system, plane system, and finally assembly of the entire part.

The CAM process systematically outlines the sequence of machining operations, beginning with roughing, followed by semi-finishing, and culminating in the finishing stage. This structured simulation not only facilitates a detailed understanding of tool trajectories, machine dynamics, and part interactions but also serves as a predictive platform prior to physical machining. By visualizing the intermediate and final states of the part, the CAM environment enables researchers to identify potential issues, such as suboptimal tool engagement or excessive material removal, before the actual machining is carried out. Such pre-emptive detection allows corrective measures to be implemented, thereby reducing the likelihood of machining errors, minimizing material wastage, and enhancing overall process efficiency. Figure 2 illustrates the complete workflow as integrated within the CAD system, whereas Figure 3 demonstrates the tool paths generated by two distinct machining strategies, namely Concentric-Multipass and Helical-Multipass. A comparative evaluation of these strategies provides critical insights into their respective capabilities in producing consistent tool engagement and optimized surface quality.

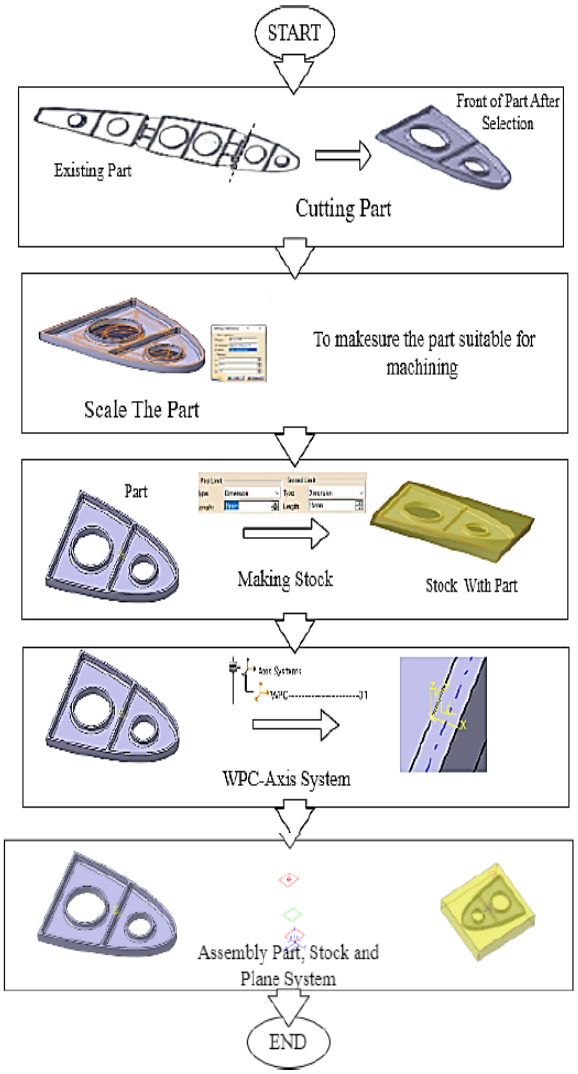


FIGURE 2. Complete workflow is integrated within the CAD system.

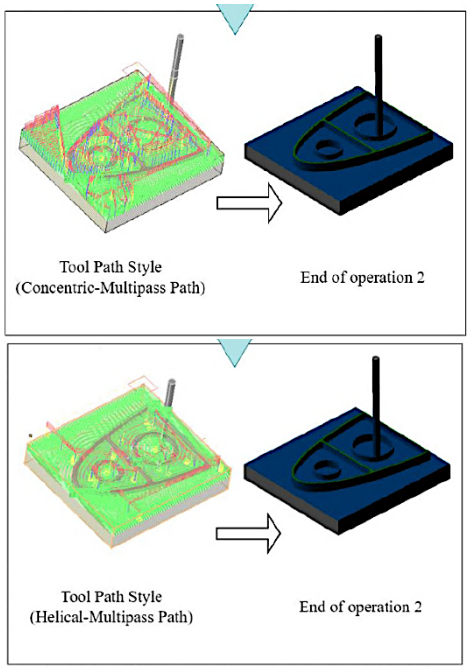


FIGURE 3. Tool paths generation of both machining strategies Concentric-Multipass (top) and Helical-Multipass (below)

MACHINING PARAMETERS AND SETUP

The 3-Axis CNC milling machine was chosen for the project because of the simple part. Aluminum 6000 series have been used in this research by selecting accordingly the material used in the aerospace or aircraft industry.

Machining parameters play a critical role in determining both process performance and the quality of the machined component. Their selection is governed by machine tool capabilities as well as the requirement to achieve the desired dimensional accuracy and surface integrity. In this study, all machining parameters were maintained constantly across all experiments to ensure a fair and controlled comparison between the selected toolpath strategies.

The machining parameters applied throughout the process are summarized in Figure 4. The key machining parameters considered include the spindle speed, feed rate and depth of cut. The spindle speed was fixed at 7500 rpm for all machining operations. This value was selected based on recommendations from tool manufacturers and supported by previous studies on milling of Aluminum 6061, which indicate that moderate-to-high spindle speeds are effective in achieving stable cutting conditions, reduced cutting forces, and improved surface finish without inducing excessive tool wear or thermal effects. Maintaining a constant spindle speed within this range also ensures process stability and repeatability across different machining strategies.

The feed rate during both approach and cutting was set at 1200 mm/min, while a higher retract feed rate of 4500 mm/min was applied to improve machining efficiency. In addition, a machining tolerance of 0.05 mm was specified for both machining strategies to ensure consistent dimensional accuracy and depth of cut is maintained at 2.5 mm each cut. The experimental design was based on a one-factor-at-a-time (OFAT) approach to isolate the effect of toolpath strategy under controlled machining conditions. Figure 5 summarizes the overall procedures carried out during the physical machining of the sample specimens.

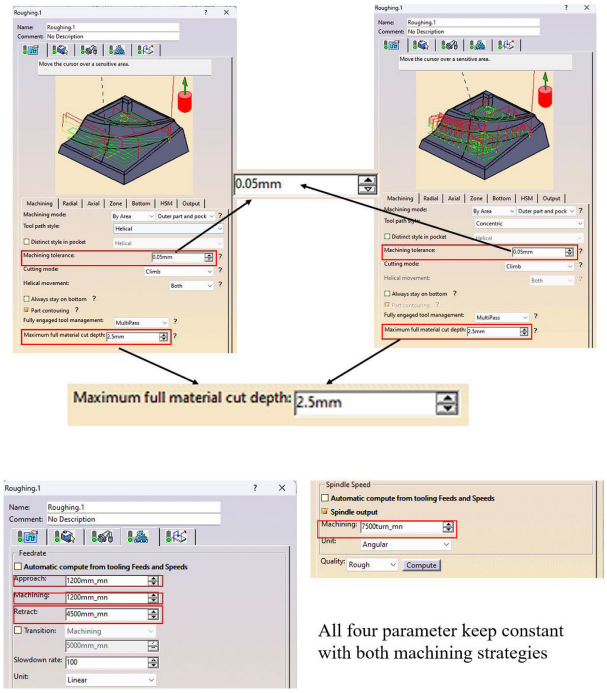


FIGURE 4. Machining parameters set in the CAM system for both machining strategies and maintained constantly for both strategies

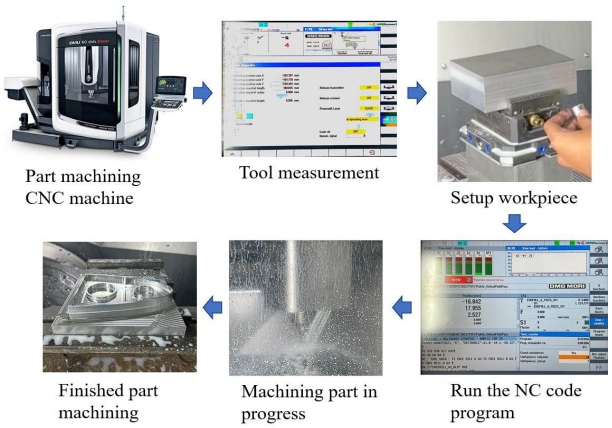


FIGURE 5. Summary of overall procedures performed during the physical machining

SURFACE ROUGHNESS MEASUREMENT AND OBSERVATION

Surface roughness test was made to collect data that can be analyzed for the best surface between both machining strategies Concentric-Multipass and Helical-Multipass. Before starting the surface roughness test, the workpiece must be setup carefully with a flat surface to make an accurate data measurement on both workpieces. The point must be at the same place on both workpieces surface area which is round surface, internal wall, and external wall as exhibited in Figure 6.

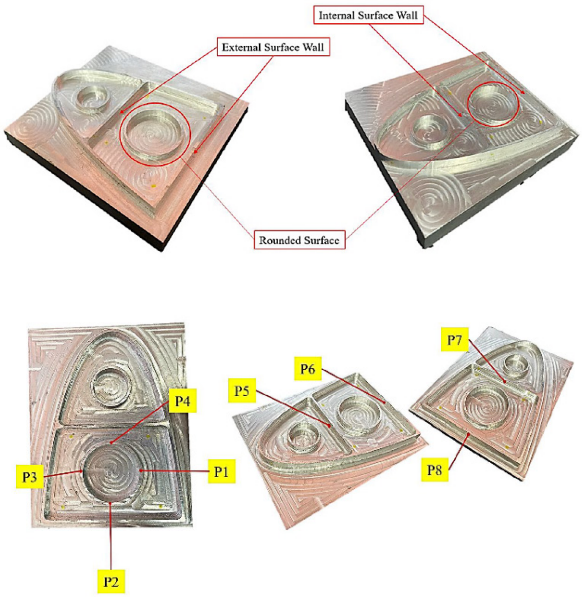


FIGURE 6. Areas or points taken for the surface roughness measurements

The surface finish of the workpiece is evaluated with a surface roughness tester, such as the Mitutoyo Surf test SJ-410. In this study, the term Ra (Arithmetical Mean Deviation) is employed to assess surface roughness. The stylus travel distance is set at 4 mm for each measurement to evaluate longitudinal surface roughness. To determine the conclusion of the surface finish on the two parts' machining, 8 points of measurement were obtained on each machined surface, and a final average Ra was produced. The roughness tester and display unit for the SJ-410 are shown in Figure 7.

In general, the permissible Ra values depend on the functional requirements of the component; however, for typical aerospace structural parts made from aluminum alloys, surface roughness in the range of approximately 0.8 µm to 3.2 µm is commonly considered acceptable, while more critical applications may require Ra values below 1.6 µm. These ranges are widely reported in manufacturing and aerospace machining literature (Kalpakjian & Schmid 2014; Groover 2016). In this study, the measured Ra values are evaluated against these established benchmarks to assess the suitability of the selected machining strategies for aerospace applications.

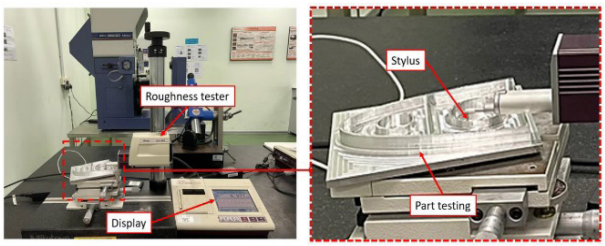


FIGURE 7. Surface roughness measurement utilizing Mitutoyo Surf test SJ-410

The surface quality of each machined cut was examined in detail using a Nikon MM-800 optical microscope, as illustrated in Figure 8. The microscope offers a magnification range from 1× to 100×, enabling precise observation of microstructural features and surface irregularities. This wide range of magnification facilitates a more comprehensive evaluation of the effects of different machining strategies on the resulting surface characteristics. Consequently, it provides valuable insights into the relationship between machining parameters and the surface integrity of the workpiece.

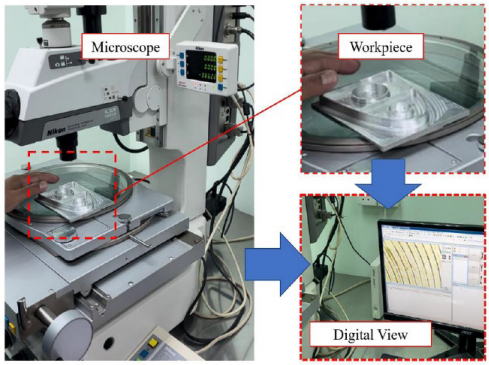


FIGURE 8. Microscopy evaluation of the machined surfaces using Nikon MM-800 optical microscope

RESULT AND DISCUSSION

SURFACE ROUGHNESS EVALUATIONS

Figure 9 and the corresponding data in Table 1 present the average surface roughness (Ra) values obtained under the Concentric-Multipass and Helical-Multipass machining strategies. A clear distinction in performance between the

two approaches can be observed. For the Helical-Multipass strategy, the highest Ra value was recorded at Point 1 (1.392 µm), followed by a gradual stabilization to values below 1.0 µm across subsequent measurement locations. This trend indicates an initial instability in tool engagement, likely associated with transient cutting conditions at tool entry, before reaching a more stable cutting regime. In contrast, the Concentric-Multipass strategy demonstrated consistently lower Ra values, with a maximum of 0.655 µm at Point 5 and a minimum of 0.3145 µm at Point 2. At the same location, the Helical-Multipass strategy produced a higher Ra value of 0.402 µm, further highlighting its comparatively lower surface quality.

The superior performance of the Concentric-Multipass strategy can be attributed to its more uniform cutter engagement and consistent chip load distribution throughout the toolpath. This results in reduced fluctuations in cutting forces and minimized vibration, which are critical factors influencing surface finish (Wojciechowski et al. 2022; Denkena et al. 2021). In addition, concentric toolpaths maintain a relatively constant radial depth of cut, promoting stable material removal and reducing the likelihood of localized surface damage. Conversely, the Helical-Multipass strategy involves a continuously varying tool engagement condition, particularly during entry and exit phases, which can induce transient force variations and localized tool deflection, leading to higher surface irregularities. Similar observations have been reported in recent studies, where non-uniform engagement in helical and spiral toolpaths contributed to increased surface roughness variability in aluminum milling (Liu et al. 2021; Silva et al. 2024).

Furthermore, the initial spike in Ra observed for the Helical-Multipass strategy may be associated with dynamic effects such as tool runout, entry impact, and chip accumulation during the early stage of cutting. As the process stabilizes, chip evacuation improves and thermal conditions become more consistent, resulting in reduced roughness values. However, despite this stabilization, the Helical-Multipass strategy did not achieve the level of surface refinement observed in the Concentric-Multipass approach.

These findings are consistent with prior literature indicating that concentric toolpath strategies generally produce better surface finishes due to their stable cutting mechanics and reduced force variability (Varga et al. 2021; Grešová et al. 2021). While helical strategies may offer advantages in terms of gradual tool entry, improved chip evacuation, and thermal management, these benefits do not necessarily translate into superior surface quality (Sun et al. 2021; Silva et al. 2024).

Overall, the results demonstrate that the Concentric-Multipass strategy is more effective in achieving lower and more consistent surface roughness in pocket milling of Aluminum 6061. This makes it a more suitable choice for aerospace applications where surface integrity and dimensional accuracy are critical. Nevertheless, the selection of machining strategies should consider specific process priorities, as Helical-Multipass may still be advantageous in scenarios requiring improved chip evacuation or reduced thermal load.

TABLE 1. Overall surface roughness data

Surface Roughness, Ra (µm)

Surface Test	Concentric-Multipass					Helical-Multipass				
Surface Round	1	2	3	4	Avg.	1	2	3	4	Avg.
P1	0.641	0.643	0.643	0.642	0.642	1.39	1.394	1.394	1.39	1.392
P2	0.322	0.316	0.3	0.32	0.314	0.416	0.402	0.393	0.398	0.402
P3	0.633	0.612	0.57	0.62	0.609	0.508	0.502	0.502	0.504	0.504
P4	0.464	0.414	0.432	0.44	0.438	0.763	0.644	0.61	0.65	0.667
Wall Inner	1	2	3	4	Avg.	1	2	3	4	Avg.
P5	0.667	0.665	0.666	0.655	0.663	0.655	0.658	0.657	0.65	0.655
P6	0.644	0.644	0.645	0.643	0.644	0.634	0.636	0.628	0.643	0.635
Wall Outer	1	2	3	4	Avg.	1	2	3	4	Avg.
P7	0.325	0.329	0.331	0.323	0.327	0.75	0.683	0.749	0.69	0.718
P8	0.36	0.366	0.364	0.36	0.363	0.88	0.974	0.969	0.9	0.931

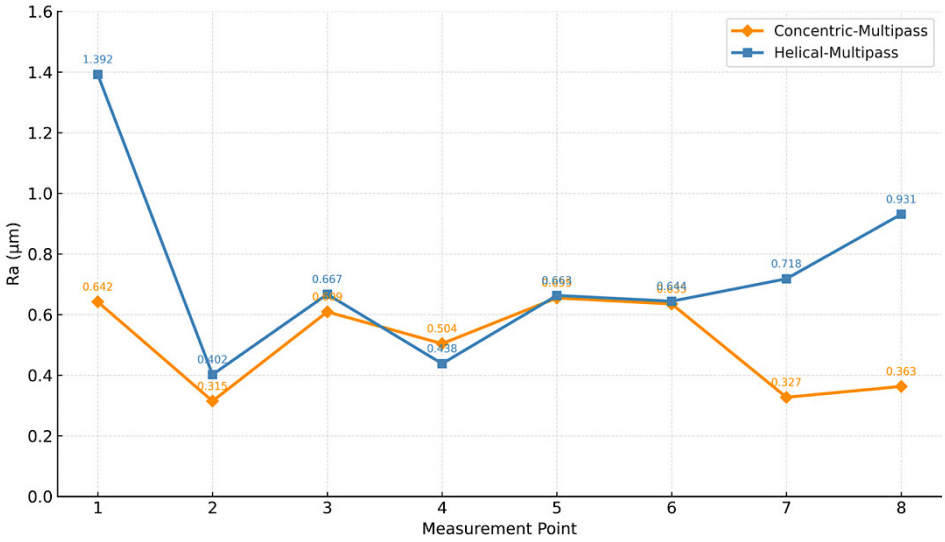


FIGURE 9. Average surface roughness (Ra) for Concentric-Multipass (top) and Helical-Multipass (below)

MIRCROSCOPY OBSERVATIONS

Figure 10 presents the optical microscopy images of the machined surfaces produced using the Concentric-Multipass (top row) and Helical-Multipass (bottom row) strategies across eight measurement points (P1–P8). The observed surface morphologies provide further insight into the material removal mechanisms associated with each toolpath strategy.

For the Concentric-Multipass strategy, the surfaces generally exhibit a more uniform distribution of tool marks with finer and more consistent feed patterns. At P1 and P2, the tool trajectories appear regular, with minimal surface defects such as micro-tearing or material pull-out, indicating stable cutting engagement and controlled chip formation. At P3 and P4, intersecting tool marks become more pronounced due to the nature of the concentric toolpath; however, the surface continuity is preserved without significant damage. Slightly increased roughness is observed at P5 and P6, where localized irregularities and darker regions suggest the presence of adhesion effects or intermittent built-up edge (BUE) formation. Nevertheless, at P7 and P8, the surface quality improves, with smoother textures and fewer deep grooves, indicating enhanced cutting stability and more consistent material removal in later tool passes. These observations are consistent with studies reporting that stable tool engagement and uniform chip load distribution contribute to improved surface integrity (Wojciechowski et al. 2022; Sun et al. 2021).

In contrast, the Helical-Multipass strategy produces more pronounced and directionally oriented feed marks across all measurement points, reflecting the continuous spiral toolpath. At P1, deeper grooves and evident material tearing are observed, corresponding to the higher Ra value measured at this location. This can be attributed to transient cutting conditions during tool entry and varying tool engagement. From P2 to P4, the surfaces appear relatively more uniform; however, the feed marks remain coarser compared to those generated by the concentric strategy. At P5 and P6, increased surface irregularities such as ploughing, micro-groove accumulation, and material smearing are evident, indicating unstable cutting conditions and higher frictional interaction at the tool–workpiece interface. At P7 and P8, elongated streaks and smeared regions suggest possible tool wear effects and localized thermal softening of the material, which are commonly associated with non-uniform engagement and fluctuating cutting forces (Liu et al. 2021; Denkena et al. 2021).

Overall, the microscopic observations strongly corroborate the quantitative surface roughness results. The Concentric-Multipass strategy consistently produces smoother and more homogeneous surfaces, whereas the Helical-Multipass approach exhibits greater variability and localized surface damage. This difference can be primarily attributed to the more stable cutting mechanics and consistent chip load in the concentric toolpath, as opposed to the continuously varying engagement conditions in helical machining. These findings are in agreement with recent literature highlighting the influence of toolpath strategy on surface integrity in milling operations (Silva et al. 2024; Varga et al. 2021). Consequently, the Concentric-Multipass strategy demonstrates superior reliability for achieving high-quality surface finishes in rough pocket milling applications. Schematic illustration comparing Concentric-Multipass and Helical-Multipass toolpath strategies in pocket milling, highlighting differences in cutter engagement, chip load distribution, cutting force stability, and resulting surface integrity. Figure

11 summarizes the major outcomes obtained from the present work which concludes the Concentric-Multipass strategy exhibits uniform engagement and stable cutting conditions, producing lower surface roughness (Ra ≈ 0.31–0.65 µm), whereas the Helical-Multipass strategy shows variable engagement and force fluctuations, leading to higher roughness (Ra ≈ 0.40–1.39 µm) and increased surface defects.

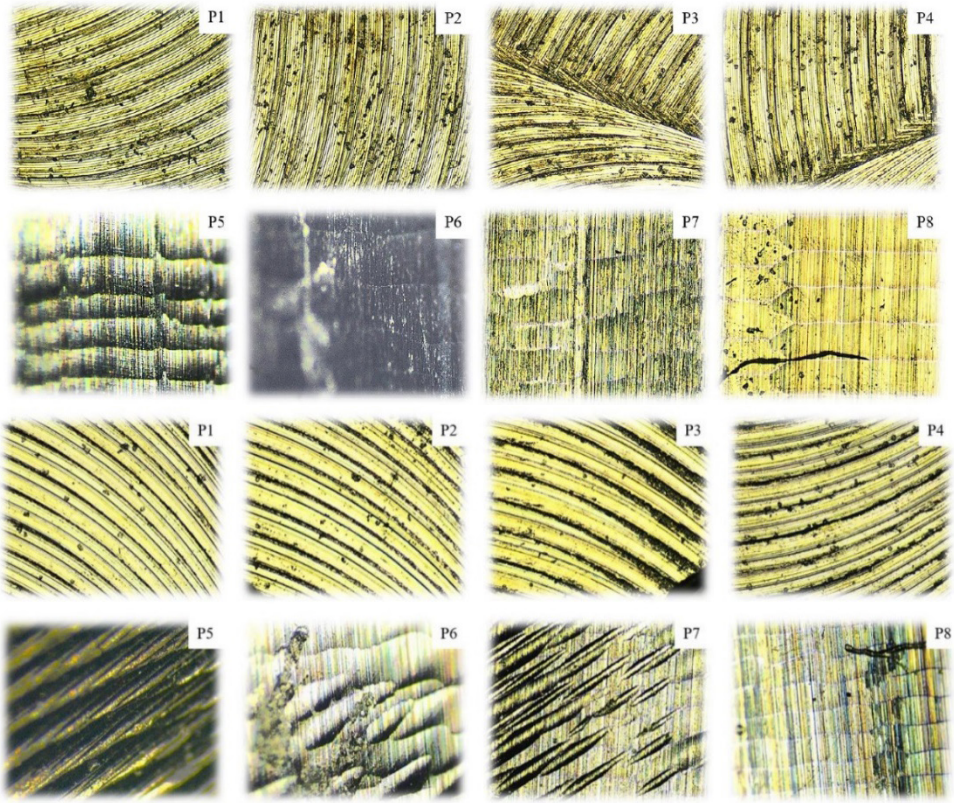


FIGURE 10. Viewpoint for Concentric-Multipass Surface Workpiece (Top); Viewpoint for Helical-Multipass Surface Workpiece (Bottom)

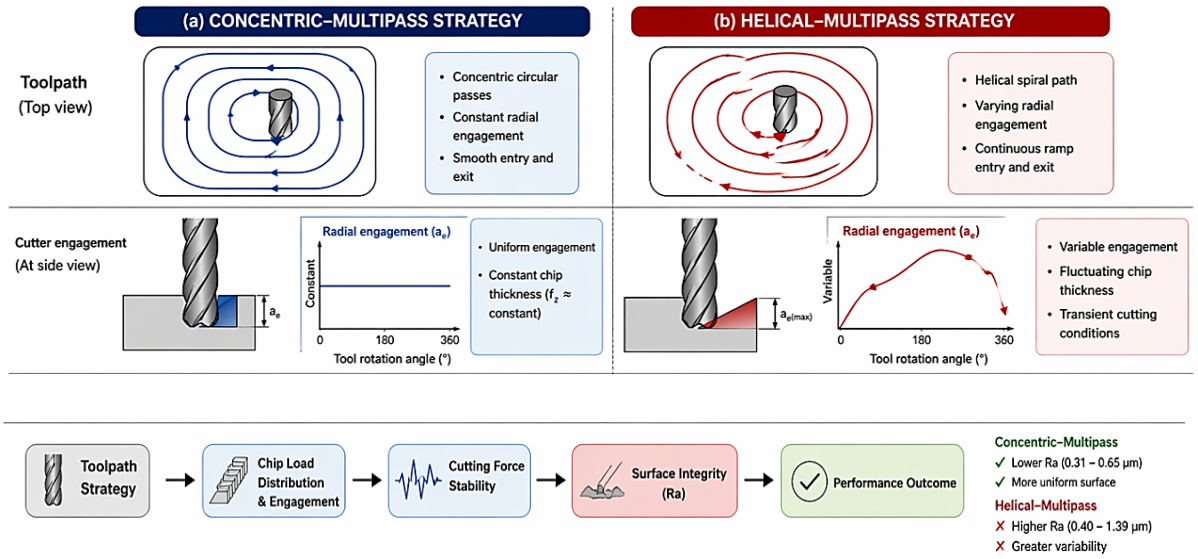


FIGURE 11. Comparative schematic of material removal mechanisms under Concentric-Multipass and Helical-Multipass strategies

CONCLUSION

This study evaluated the influence of toolpath strategies on surface integrity during pocket milling of Aluminum 6061 using Concentric-Multipass and Helical-Multipass approaches under constant machining conditions. The results demonstrate that the Concentric-Multipass strategy consistently produced superior surface quality, achieving a minimum surface roughness (Ra) of 0.3145 µm and a maximum of 0.655 µm, compared to the Helical-Multipass strategy which recorded a higher peak value of 1.392 µm. Overall, the Concentric approach yielded surface finishes that were approximately 20–50% smoother across all measured regions.

Optical microscopy observations further confirmed that Concentric-Multipass generated more uniform tool marks with reduced defects such as ploughing, micro-tearing, and material smearing, whereas Helical-Multipass exhibited greater variability and localized surface damage. These findings indicate that the stability of tool engagement and consistent chip load distribution in the Concentric strategy play a critical role in enhancing surface integrity.

Collectively, the results indicate that Concentric-Multipass offers a more reliable machining strategy for achieving high-quality surface integrity in rough pocketing operations. From an industrial perspective, this outcome suggests that the Concentric-Multipass approach may be particularly advantageous in sectors such as aerospace and precision engineering, where superior surface quality is essential to ensure component durability, functional performance, and dimensional stability. By minimizing the need for extensive finishing operations and reducing material wastage, the Concentric-Multipass strategy has the potential to improve overall machining efficiency, reduce production costs, and enhance process sustainability.

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DECLARATION OF COMPETING INTEREST

None.

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