

Study of Microchannel Machining Rates in Aerospace Grade Aluminum by using CAD-CAM Integration System

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Abstract

Micromachining has experienced a vast growth and is forecasted to be growing in next few decades especially in the semiconductor, nuclear and aerospace industries. Although there are multiple techniques of micromachining such as laser micromachining, chemical erosion, wire electrical discharge machining, micro-milling etc., in this study micromachining by CNC milling is analyzed and experimented. Initially, a theoretical analysis is performed by using CAD-CAM integration process considering machining rate and surface roughness as outputs. Based on this theoretical analysis, a practical experiment is conducted to observe cutting tools life and surface finish of the part while machining micro-channels in an aerospace grade aluminum. Tool wear is observed by varying feed rates keeping other cutting parameters as constant. In general, higher machining rate is achieved by higher spindle speed and feed rate but an inconsistency is observed in practical machining that needs further verification. Surface finish is found to be better at higher spindle speed at lower feed rate. A comparison between theoretical analysis and practical experimentation is also illustrated in this article.

Keywords

Micro-machining, CAD-CAM Integration, Tool Wear, Micro-channel

1. Introduction

Micro milling is a mechanical manufacturing process used to create a micro level intricate features and complex geometry on a part by using a tiny cutter. With the pace of industrial revolution, manufacturing process continuously gets upgraded with onward requirements and demands. As a part of that upgradation, traditional sectors such as research laboratories, nuclear industries, aerospace industries etc. step forward to curtailing the activities for producing the components and parts with minimum amount and number of raw materials and tools respectively (*Micromachining Industry Analysis And Insights Report 2025*, n.d.). In that background, the micro-machining process has become an essential part of modern manufacturing that enables fabrication of complex and miniature level parts with higher precision, greater quality, and improved functionality (Schmidt et al., 2002) specially for machining intricate feature of injection mold (Bissacco et al., 2005). But there are enormous challenges in this journey for achieving a consistent quality by minimizing tool wear, maintaining dimensional accuracy, and controlling process parameters. To overcome those challenges, micromachining has been an intensive and undivided concentration among the researchers, scientists, manufacturing engineers and machinists. A good deal of research has been conducted in the past on this

very particular technology and this ongoing exploration continues to advance the evolution of micro-machining techniques to play crucial role in the current and upcoming manufacturing industries. Particularly, A J Mian et al. investigated the micro-machinability of multi-phase ferrite-pearlite steel with a large grain size to get cutting performance of the tools by analyzing the effect of chip thickness, tool edge radius and grain size(Mian et al., 2009). The type of metal whether it is isotropic or anisotropic and metal’s crystallographic orientation also affects the performance of micro-machining (Leer & Zhou~t, 1993).

Furthermore, B Martin et al. and K Cutting et al. observed and optimized the tool life while machining with micro end mills under certain cutting conditions (Cutting et al., n.d.; Martin et al., 2013). Then numerous research has been carried out to find optimized machining parameters and cost optimization while maintaining surface quality and metal performance such as E. Vazquez et al. analyzed machining parameters and implemented it to manufacture microchannel by using micro milling to prove its suitability and hence ensuring the surface finish and quality of those micro channels in different metals (Vázquez et al., 2010). Yuan gao et al., M. Dobrzynski et al. and D. J. Cheng et al. worked to find a combination of machining parameters specifically spindle speed and cut path for compensating machining deformation of micro-parts which are normally difficult to machine(Gao et al., 2016), (Dobrzynski et al., 2018)(Cheng et al., 2020). These optimizations micro milling in micro parts directly contributed to the tooling cost reduction by either saving cutting tool life or reducing cycle time(*Effect of Machining Feed on Surface Roughness in Cutting 6061 Aluminium*, n.d.; Kang & Ahn, 2007). In that sequence, this study is carried out to take part in this new avenue of research. The efforts here include the application of CAD CAM integration in machining parameter optimization to manufacture microchannels of cutting edge thermal mechanical components in cost effective way by maintaining appropriate surface quality, increasing machining rate and maximizing tool life.

1.1 Objectives

The objective is to compare theoretical CAD-CAM analysis with experimental results of CNC micromachining to assess machining rate, surface finish, and tool life.

2. Materials and Methods

2.1 Material

The work piece material tested in this study was Aluminium-6061 T6 of hardness 20 HRB which is an aerospace grade aluminum where cooling rate is crucial for microstructural improvement of the parts in designing the components especially in aerospace application (Rahman et al., 2025). The chemical composition of the steel received as MTC (Mill Test Certificate) from the vendor is listed below in Table 1. The dimension of the work piece is 0.125 inch thick, 14 inch wide and 20 inch in length. As the thickness is too low, to maintain the stability during machining, the work piece was mounted with a vacuum fixture of size L-30-inch X W-20 inch. Total 250 microchannel was designed on the plate considering continuous tool path. The microchannel length is 18.5 inch. The width of the microchannel is kept same as cutter diameter 0.03 inch. Detailed drawing of the panel with microchannel is shown in Figure 1.

Table 1. Chemical composition of Aluminium-6061 T6

Element	Fe	Mn	Si	Cu	Mg	Cr	Zn	Ti	Al
Wt. %	≤0.7	≤0.15	0.4-0.8	0.1-0.4	0.8-1.2	0.04-0.35	≤0.25	0.004	Rest

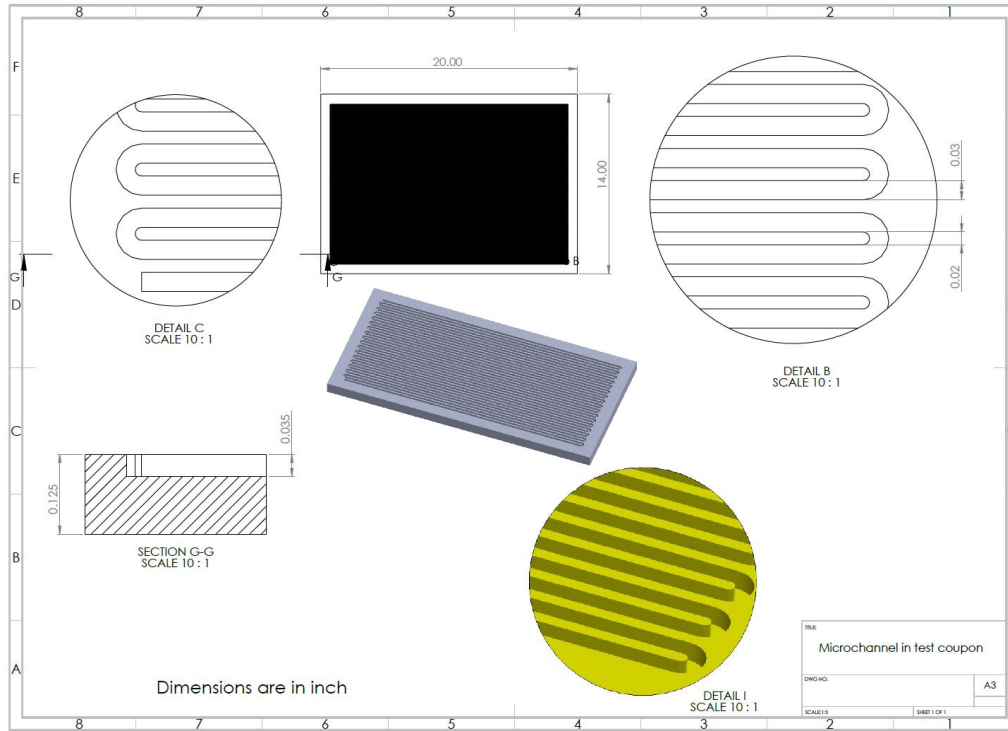


Figure 1. CAD drawing of a complete panel with 250 Microchannels

2.2 Methodology

For theoretical analysis, machining time is recorded from toolpath verification and simulation. After that, surface roughness and machining rate was calculated by using below equations.

Milling machine material removal rate,

$$MRR = d \cdot a_p \cdot F \cdot n \cdot N \quad (1)$$

$$Ra = \frac{0.0642}{d} \left(\frac{F}{n} \right)^2 \quad (2)$$

Where

Ra = Arithmetic mean surface roughness in $\mu\text{in.}$ or $\mu\text{m.}$

F = is the feed rate in in/min

n = is the spindle speed in rpm

N = is the number of teeth on the cutter

d = is the cutter diameter in inches or mm

a_p = is the depth of the cut in inch

2.3 CAD CAM Integration Process:

For CAD-CAM integration Master CAM 5 database was used. Figure 2 shows the machine selection and cutting parameters input in database. There were several default machines assigned in database, but milling machine-inch was used for this analysis.

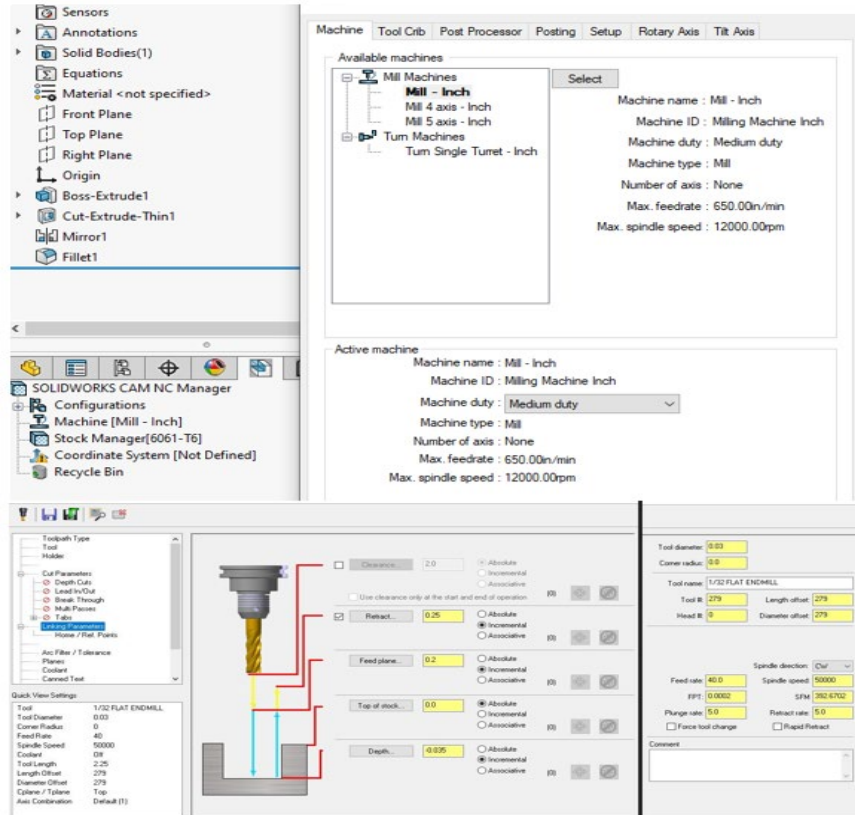


Figure 2. Defined machine and cutting parameters for CAM programming

Although there is built in data for spindle speed and feed of the machine, these can be customized based on the cutter selected. Tool length offset compensation number mentioned here is 279 but during practical experimentation the operator is instructed to set it up according to machine to be used for the experimentation. Depth of cut is considered full depth of the channel 0.035 inch for this analysis. While suitable feed rate, plunge rate and retract rate are set automatically, those data can be customized considering final part finish and quality requirements.

In the second step of CAD-CAM integration, machining operation plan and toolpath is generated as shown in Figure 3. Once toolpath is generated, total feed length and machining time can be estimated from database.

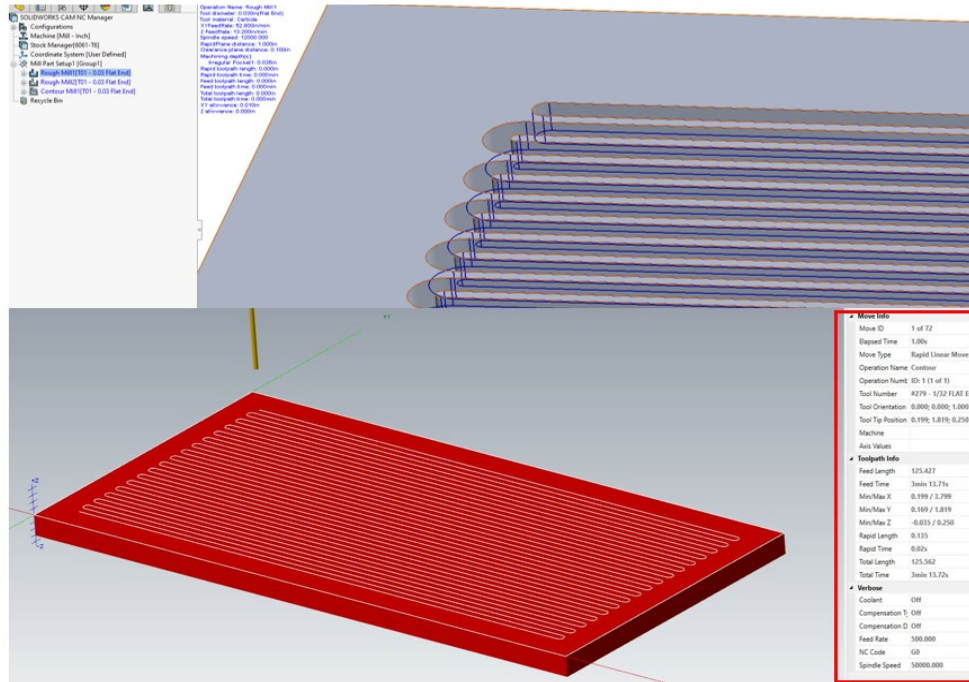


Figure 3. Tool path generation using CAM database

Sequentially, for verification of toolpath, simulation is done prior to generating NC code for the machining (Figure 4). Through this verification, we can adjust tools, dimension, coordinate system etc. Finally, G code and M code is generated by using post processor of Master CAM data base. Basically, it creates coordinates for cutter movement in different location of the workpiece in linear and circular path. As, NC code is very machine specific, several adjustments in code had to be maintained based on machine specifications during practical machining. For optimization of theoretical data, post processor interface of master CAM was used (Figure 5) by which we have changed our input such as feed rate, spindle speed, cutter geometry to observe, derive and record the output such as machining time, material removal rate, surface roughness etc.

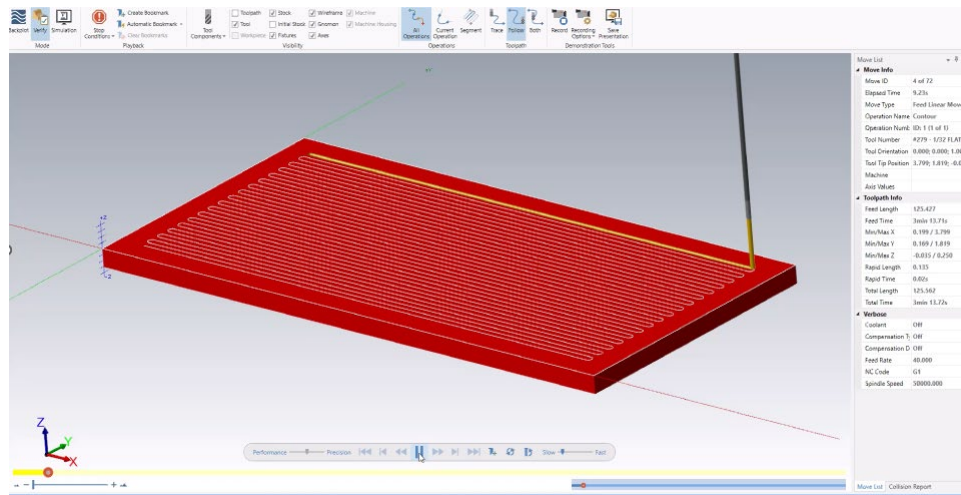


Figure 4. Demonstration of a toolpath simulation

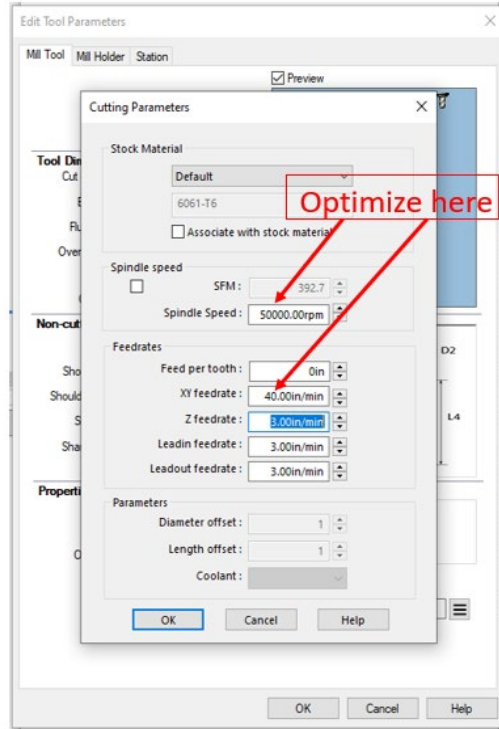


Figure 5. Demonstration of a toolpath simulation

3. Experimental Procedure

3.1. Machine and Cutting Tool

For experimentation, a linear 3 axis CNC milling of model “Haas VF-2” with wireless probing system was used which is equipped with a Nakanishi HES810 model vertical spindle integrated with a load meter. The load meter is useful to observe the loading condition of the spindle while machining and changing machining parameters.

The cutting tool used in this study was from Harvey tool. It’s a 2-flute carbide cutter without any coating. Detailed dimensions along with a tool pre setter is shown in Figure 6. The tool pre setter from Haimer is used only to measure the tool run out.

Cutting Tool Manufacture	Cutting Tool Model	Coating Type	Corner Radius	Cutting Diameter	Flute Length	# of Flutes
Harvey Tool	#13930	None	None	.0300	.0450	2



Figure 6. Harvey Cutting tool along with a Haimer tool pre setter

3.2. Practical data collection strategy

The strategy planned for collecting data includes set up the design variable such as feed rate, tool size, coated and uncoated tools, spindle speed. Secondly, a fast failure process is implemented such that a tool will be run for 3 times at highest assumed feed rate or to the machine maximum allowable feed rate to determine average fast failure point. In this experiment, starting feed rate was 150 IPM, then played back and forth with 90% and 80% of this starter to

find a suitable average. For the sake of analysis, maximum linear inch of a microchannel was observed and recorded at which a tool has sustained before failure by calculating the number of panels and channels.

4. Results

A total number of 26 microchannels were considered for theoretical analysis. Constant input parameters were width and depth of cut along with other constant parameters such as coating, coolant and constant of surface roughness calculation. Table 2 below represents the constants and variables for input and output and in Table 3 theoretical data sets are organized.

Table 2. Input and output parameters

Parameters	Input	Parameters level	Output
Constant parameters	Width of cut	0.03	Machining time
	Depth of Cut	0.035	Material Removal rate
	Coating	No	Surface Roughness
	Surface-roughness constant	0.0642	
	Coolant	Flood	
Variable parameters	Spindle speed	50,000; 80,000	
	No of Flute	2	
	Feed rate	40-160IPM with 10 intervals	

Table 3. Theoretical Data (Plan for experimentation)

Constants							
Flutes	Corner Radius	Coating	RPM	Width of cut	Depth of cut	Coolant	Constant
2	None	None	50000	0.03	0.035	Flood	0.0642
4							
	Input			Output, 2 flutes			Output, 4 flutes
Test	Spindle Speed RPM	Feed (in/min)	Chip load by cutter diameter	Machining time, Min	MRR inch ³ /min	Ra, micrometer	MRR inch ³ /min
1	50000	40.0	0.0004	115.8	4200	0.03478784	8400
2	50000	50.0	0.0005	103	5250	0.054356	10500
3	50000	60.0	0.0006	93	6300	0.07827264	12600
4	50000	70.0	0.0007	84	7350	0.10653776	14700
5	50000	80.0	0.0008	77	8400	0.13915136	16800
6	50000	90.0	0.0009	71	9450	0.17611344	18900
7	50000	100.0	0.001	66	10500	0.217424	21000
8	50000	110.0	0.0011	62	11550	0.26308304	23100
9	50000	120.0	0.0012	58	12600	0.31309056	25200
10	50000	130.0	0.0013	54	13650	0.36744656	27300
11	50000	140.0	0.0014	51.5	14700	0.42615104	29400
12	50000	150.0	0.0015	49	15750	0.489204	31500

13	50000	160.0	0.0016	46.5	16800	0.55660544	33600
14	80000	40.0	0.00025	115.8	6720	0.013589	13440
15	80000	50.0	0.0003125	103	8400	0.02123281 3	16800
16	80000	60.0	0.000375	93	10080	0.03057525	20160
17	80000	70.0	0.0004375	84	11760	0.04161631 3	23520
18	80000	80.0	0.0005	77	13440	0.054356	26880
19	80000	90.0	0.0005625	71	15120	0.06879431 3	30240
20	80000	100.0	0.000625	66	16800	0.08493125	33600
21	80000	110.0	0.0006875	62	18480	0.10276681 3	36960
22	80000	120.0	0.00075	58	20160	0.122301	40320
23	80000	130.0	0.0008125	54	21840	0.14353381 3	43680
24	80000	140.0	0.000875	51.5	23520	0.16646525	47040
25	80000	150.0	0.0009375	49	25200	0.19109531 3	50400
26	80000	160.0	0.001	46.5	26880	0.217424	53760

For example, practical experimentation was done by using 2 flute cutters only at 80,000 spindle speed with feed rate 130 and 150 IPM. Machining rate is calculated in terms of cutting length instead of material removal rate. Surface roughness is observed and recorded by using Keyence profilometer. All these experimental data are highlighted in Table 4 for further analysis. Table 5 and Table 6 indicate the comparative data between theoretical analysis and practical experimentation.

Table 4. Experimental Data

Constants						
Flutes	Corner Radius	Coating	RPM	Width of cut	Depth of cut	Coolant
2	None	None	80000	0.03	0.035	Flood
	Input			Output, 2 flutes		
Test	Spindle Speed (RPM)	Feed (in/min)	Chip load by cutter diameter	Cut length (inch)	Cutting Time (min)	Surface Roughness, Ra (micron)
1	80000	130.0	0.0008125	4625.0	36.00	24.13
2	80000	130.0	0.0008125	32375.0	250.00	24.13
3	80000	130.0	0.0008125	18.5	1.00	24.13
4	80000	150.0	0.0009375	0.0	0.00	23.88
5	80000	150.0	0.0009375	4625.0	31.00	23.88
6	80000	150.0	0.0009375	92.5	1.00	23.88
7	80000	150.0	0.0009375	101750.0	679.00	23.88

Table 5. Comparative data between theoretical and actual cutting time

Test	Input		Output, 2 flutes				
	Spindle Speed (RPM)	Feed (in/min)	Cut length (inch)	Cut length (feet)	No of panels	Theoretical Cutting time, (min)	Actual Cutting Time (min)
1	80000	130	4625.0	385.4	1.0	54	36
2	80000	130	32375.0	2697.9	7.0	378	250
3	80000	130	18.5	1.5	0.004, 1/250	0.2	1
4	80000	150	0.0	0.0	0.0	0	0
5	80000	150	4625.0	385.4	1.0	49	31
6	80000	150	92.5	7.7	0.02, 1/50	0.98	1
7	80000	150	101750.0	8479.2	22.0	1078	679

Table 6. Comparative data between theoretical and actual surface roughness

Test	Input		Output, 2 flutes	
	Spindle Speed (RPM)	Feed (in/min)	Ra, Theoretical (micron)	Ra, actual (micron)
1	80000	130	0.143533813	24.13
2	80000	130	0.143533813	24.13
3	80000	130	0.143533813	24.13
4	80000	150	0.191095313	23.88
5	80000	150	0.191095313	23.88
6	80000	150	0.191095313	23.88
7	80000	150	0.191095313	23.88

5. Discussion

Table 2 presents spindle speed, feed and chip load as input and machining time was recorded from the toolpath simulation. MRR and surface roughness were calculated by using equation 1 and 2 respectively as mentioned in methodology section. The feed rate vs MRR plot (Figure 7) indicates that the machining rate can be maximized with the increased feed rate and can be further increased with higher spindle speed and higher no of flutes.

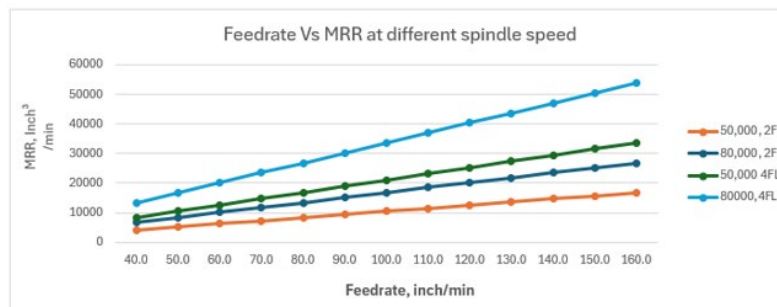


Figure 7. Feed Rate Vs MRR graph

On the other hand, Figure 8 shows that, the lower the feed rate, the higher the surface finish. From this theoretical analysis, the author wants to claim higher no of flutes, higher spindle speed and lower feed rate as optimized parameters while feed rate can be optimized based on surface quality requirement. At the same time, this statement is considered as the base case for this experimentation to carry forward.

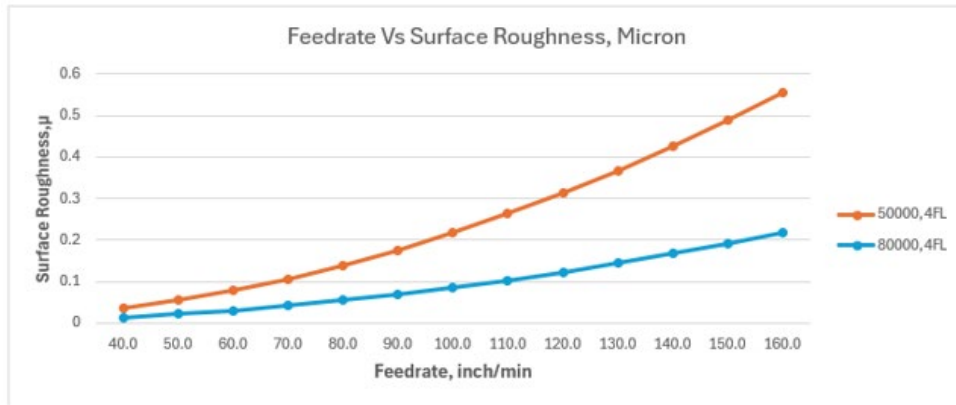


Figure 8. Feed Rate Vs Ra graph

Moving to experimental analysis, Figures 9 and 10 present the plot of cut length and cutting time in terms of feed rate. It's obvious that as $R^2 < 1$, the correlation between feed rate and cut length is not good. This suggests that more data are required to establish a stronger correlation.

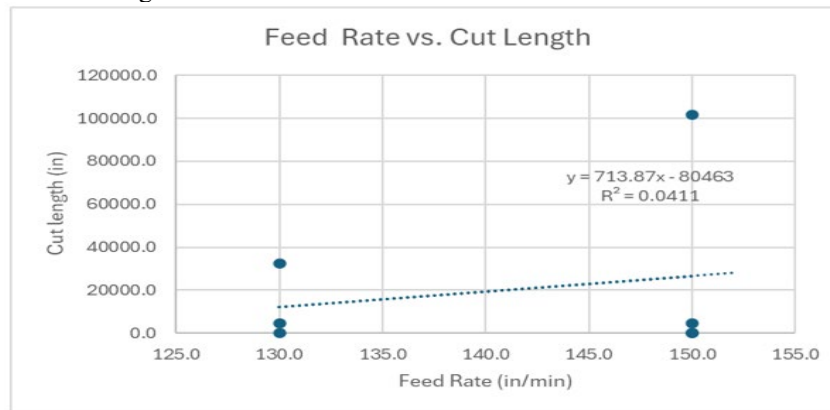


Figure 9. Feed Rate Vs cut length graph

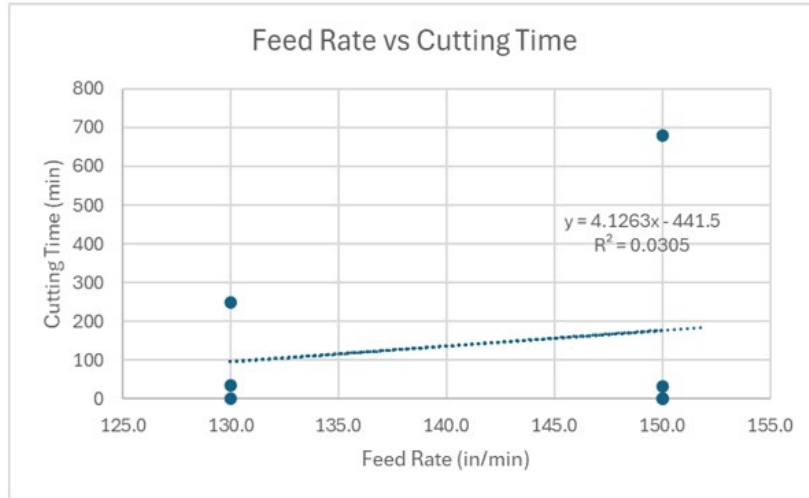


Figure 10. Feed Rate Vs cutting time graph

However, from this analysis, one can at least quantify how many cutters might be required to machine the part and it gives the idea of what feed rate might be suitable to minimize the risk that tool wears out overnight prior to completing the product.

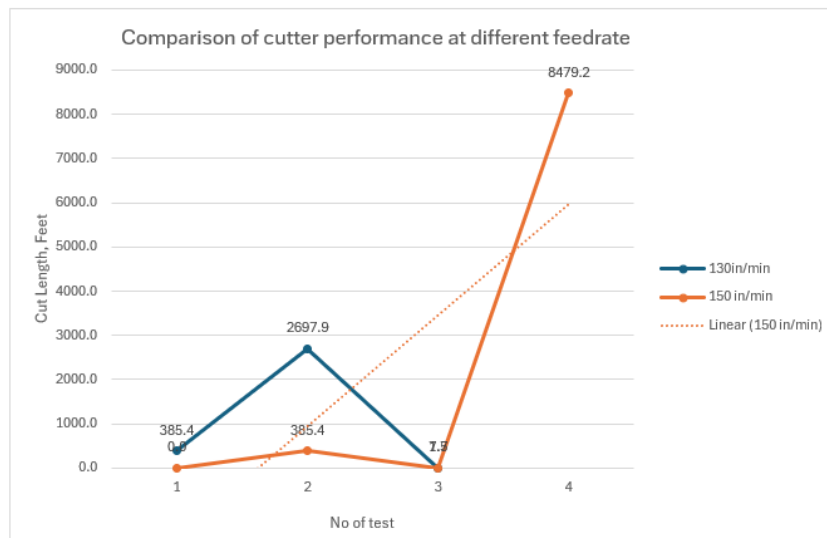


Figure 11. No of test Vs cutting length

Figure 11 stipulates the cutting length for different tests and at different feed rate. Inconsistency in test 3 is observed and is hypothesized to be the presence of worn edge in the tool 3. It also suggests the importance of tools inspection before machining.

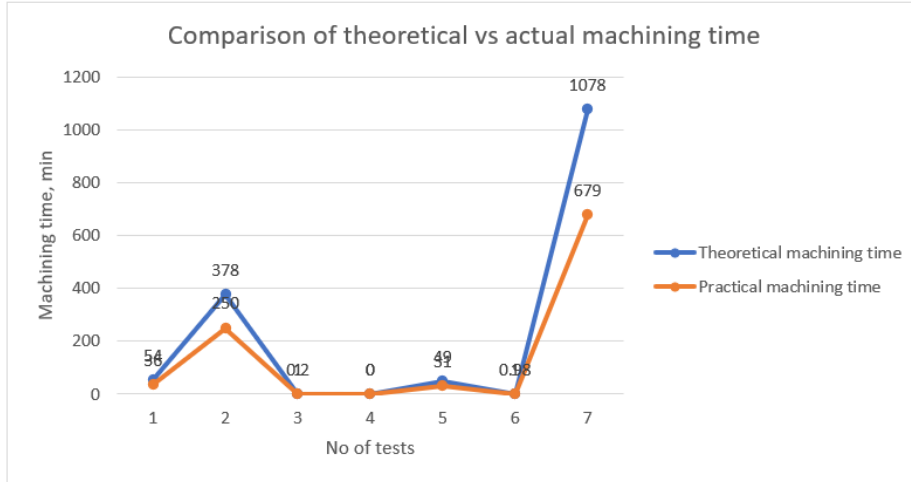


Figure 12. No of test Vs machining time graph

A comparative analysis is performed to understand the deviation of actual machining time with theoretical machining time (Figure 12). It states that actual machining time outperformed than theoretical machining time. This could be due to high-quality, precise machine tool and the quality of cutting tools itself. High quality, precise machine tools outperform machining time by enabling faster cutting speeds, fewer tool changes, and reduced rework through better stability, accuracy, and real-time adjustments. This also prevents errors and waste and ultimately keeping machines running continuously for higher throughput. Nevertheless, author still suggests for appropriate clarification with additional tests as a resolution of this situation.

Another study is performed to compare surface roughness value of aluminum between theoretical and actual machining part. Figure 13 shows the experimental surface roughness profile performed on the machined part by using Keyence surface roughness profilometer. The graph plotted in Figure 14 explains the major abnormalities between theoretical and practical surface roughness measurements.

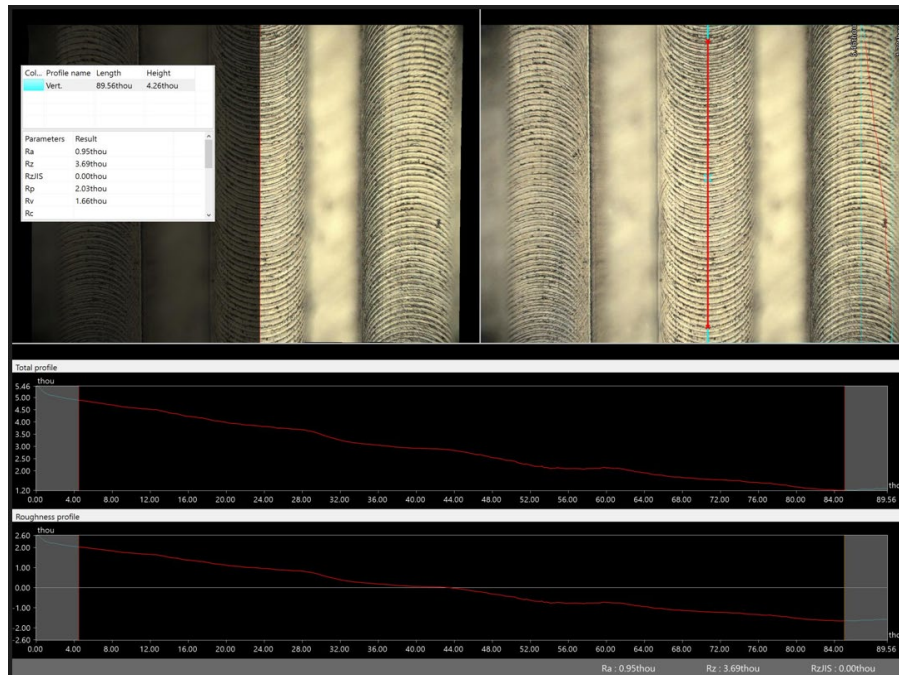


Figure 13. Surface roughness profile of machined aluminum microchannel

While the literature points out the range of surface roughness in a machined aluminum as $0.5\text{-}3\mu$ (*Effect of Machining Feed on Surface Roughness in Cutting 6061 Aluminium*, n.d.), the roughness observed in this study was significantly higher-reaching values nearly eight times above the expected range. This deviation can be caused due to a combination of several machining related factors, including the calibration of profilometer, due to worn tool edges described earlier to explain Figure 11, inadequate control of machine vibration etc. Built up edge formation on cutting tool over time also could lead to the surface irregularities. To resolve this, author suggests considering the flow of the cutting fluid, proper inspection of the tools from time to time, ensuring the stability in fixturing system to control vibration in any future studies. All these efforts collectively can improve the surface smoothness of the intricate microchannel while machining.

As a whole, the author recommends revisiting the theoretical model to assess whether the existing equations for predicting surface roughness and machining time require modification by considering some factors for this specific case. While the classical machining models rely on idealized assumptions such as stable cutting conditions, standard machining parameters, and uniform material properties-these may not be applicable always for the real operating environments. In the situation of intricate micro-machining, the conventional formulas may under predict roughness and inaccurately estimate machining time. Therefore, refining or customizing the theoretical models by incorporating correction factors or empirical coefficients would provide more accurate predictions and better alignment with experimental results.

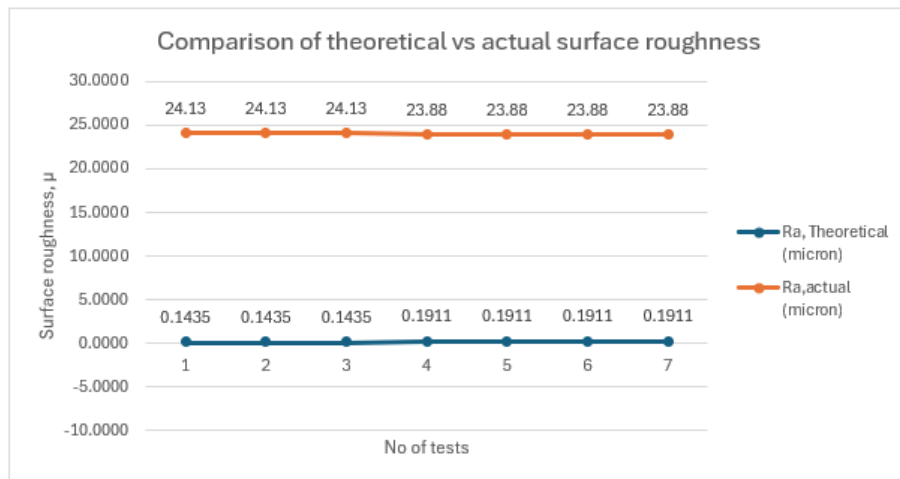


Figure 14. No of test Vs surface roughness

6. Conclusion

In this study, machining rate and surface quality have been investigated both theoretically and practically. Generally, it can be concluded that standard machine tool can produce microchannels. Despite having some discrepancy in practical experiment due to limitations in experimental setup, the effect of machining parameters on machining rate and surface quality have been heavily realized in this study. The authors recommend this study to be further extended with more variations in feed rate, spindle speed, no of flutes of the cutter for genuine validation as suggested by theoretical interpretation. In addition to this, author recommends reviewing the theoretical model further to assess any requirement of modification for the specific case by considering the correction factors with the equation of surface roughness and machining time. This would ensure accurate predictions and better alignment with the experimental outcomes. The authors also propose to continue this research on different metals and cutting tools materials for precise optimization.

7. Acknowledgement

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Biographies

Md. Bahar Uddin is currently pursuing his Master's degree in Manufacturing Engineering at Missouri University of Science and Technology, USA, starting in August 2023. He earned his Bachelor of Science in Mechanical Engineering from Khulna University of Engineering and Technology (KUET), Bangladesh, in 2011. Prior to his graduate studies, he gained extensive industrial experience working in one of the largest plastic manufacturing companies, where he was actively involved in injection molding, tooling, and polymer processing. His combined academic background and hands-on experience gave him a strong foundation in both theoretical and applied aspects of manufacturing systems. His areas of expertise include plastic product development and mold manufacturing, CAD/CAM-based tooling, injection and blow molding operations, polymer processing, CNC/EDM machining, and DFM analysis. He also brings experience in sourcing, procurement, quality inspection, and factory operations management. Bahar has led and contributed to several projects focused on productivity enhancement, cost optimization, and feasibility analysis for mold and product design. His current academic and research interests include advanced manufacturing technologies, 3D prototyping, simulation-based design, and sustainable production systems. Md. Bahar Uddin is passionate about integrating industrial best practices with academic research to create innovative, efficient, and cost-effective manufacturing solutions.

Abdul Halim is currently serving as a Lecturer in the Department of Industrial and Production Engineering at Bangladesh Army University of Science and Technology (BAUST), Saidpur, Bangladesh. He is pursuing his Master of Science (M.Sc.) in Industrial and Production Engineering at Rajshahi University of Engineering and Technology (RUET), where he also completed his Bachelor of Science (B.Sc.) in the same field in 2023. Before joining academia, Abdul Halim gained valuable industry experience at DBL Group, one of Bangladesh's leading industrial conglomerates. During his tenure in the Supply Chain and Production Planning Department, he was actively involved

in materials planning, scheduling, and supply chain. His primary research interests include additive manufacturing, supply chain management, operations research, product design, and quality control. He is particularly focused on bridging the gap between theoretical optimization models and practical industrial applications. Through his academic role, he is also involved in guiding undergraduate projects and promoting research in emerging manufacturing technologies and production systems.