Journal of Mechanical Engineering Science and Technology
Vol. 9, No. 1, July 2025, pp. 114-125

Toolpath Motion Strategy and Feed Rate in CNC Milling on Energy Consumption of Machining Process

Luqman Dwi Saputra*, Eko Yudiyanto

Department of Mechanical Engineering, Malang State Polytechnic,
Jl. Soekarno Hatta No. 9, Malang, 65141, Indonesia
**Corresponding author: luqmandwisaputra35@gmail.com*

Article history:
Received: 7 March 2025 / Received in revised form: 20 April 2025 / Accepted: 27 April 2025
Available online 6 May 2025

ABSTRACT

The use of CNC milling machines to produce components, especially aluminum brackets used for automotive, is one of the advances in the industrial field. The use of CNC milling machines has the advantage of producing processes with speed accuracy, and better workpiece quality than conventional machines. This research investigates energy consumption in the CNC milling process by varying the toolpath motion strategies—Zigzag, Constant Overlap Spiral, Parallel Spiral, and Parallel Spiral Clean Corners—as well as feed rates of 700 mm/min, 800 mm/min, 900 mm/min, and 1000 mm/min. The goal is to find out the best parameters for using energy in the machining process. The material used in this research is Aluminum 6061. The shape tested is a bracket. The simulation was conducted to determine the machining process time using Mastercam software. The simulation results indicate that the Zigzag toolpath motion strategy at a feed rate of 1000 mm/min produces the lowest energy consumption (307.620 Kilojoules) whereas the Parallel Spiral Clean Corners toolpath at a feed rate of 700 mm/min produce the highest energy consumption (457.142 Kilojoules). The selection of appropriate machining parameters has a significant influence on the efficiency of processing time and production costs. By selecting the right toolpath motion strategy and feeding parameters, the manufacturing industry can increase productivity and reduce production costs more effectively.

Keywords: *CNC milling, energy consumption, feed rate, machining time, simulation, toolpath motion.*

I. Introduction

Computer numerical control (CNC) milling machines are equipped with technology that utilizes programmed software to control the operation, movement, and precision level of machine tools. This software is integrated with the machine, enabling automatic operation on various tools such as milling machines, lathes, drills, and others [1]. The purpose of using CNC milling machines is to facilitate the manufacture of products with various dimensions and complex shapes. CNC can operate continuously and produce large quantities. CNC operates in a measured manner and produces good quality [2]. Therefore, CNC milling machines have been widely used in the manufacturing industry in recent years [3], especially for aluminum bracket products, where rising demand and increasingly complex shapes have necessitated their use. The CNC milling machining process can produce holes and geometric shapes that are quite complicated. Consumers demand the aesthetics and function of aluminum brackets to support the structure of motorized/automotive vehicles. In automotive components, aluminum is used for engine components, brackets, and accessories. Bracket products have many variations in shape to adjust the development of automotive design [4]. The aluminum bracket production process uses CNC milling machines to form components.

DOI: 10.17977/um016v9i12025p114

The design develops according to consumer demand with complex accuracy and good quality results [5], [6].

Machining processes account for a large portion of the total energy consumption in the manufacturing sector. The machining process is important to save energy and provide important information to the CNC operator to improve the energy efficiency of the machine. Machining time optimization is a crucial factor in improving efficiency as well as process performance on CNC machines [7]-[9]. Some machining parameters in CNC milling that can affect machining time are feed rate, spindle speed, depth of cut, and toolpath motion. The selection of parameters on the variation of feed rate will have an impact on the quality of machining results and machining time, which will also have an impact on costs in the production process [10]-[13]. Toolpath motion optimization using Mastercam software can help to measure machining time and reduce machining time significantly [11]. The toolpath motion simulation process can provide other benefits, such as avoiding collisions between the tool and the workpiece and determining the machining time for each production process. Simulation can increase productivity and optimize costs before the production process [14], [15]. Simulation methods are widely used in manufacturing processes due to their ability to produce results comparable to experimental processes [16]. Simulation software programs have been developed to graphically verify instruction programs before running parts on machine tools with actual workpieces [17].

This study complements the shortcomings of previous research that have not presented energy consumption, as in the research of Pajaziti *et al.* (2025), which only explains the machining time and toolpath motion strategy [1]. In other research that explains the optimization of CNC milling machine machining parameters on the quality of results and machining time [2],[3],[13]. Camposeco-Negrete's research explains the optimization of energy consumption and surface roughness on Slot Milling Machines [7]. From the previous research, the study presents a simulation of the machining process on a CNC milling machine by varying the feed speed and toolpath movement on Aluminum 6061 material. The resulting product is a bracket. This method can predict the machining time required for the machining process, specifically to produce the product. Machining time for each parameter variation is obtained through simulation using MastercamX5 software. This software allows the simulation of the machining process to verify the accuracy of the project before it is implemented. The machining time is further verified by experiments using the machine to determine the energy consumption required in the bracket production process. The purpose of this research is to determine the best parameters to obtain a short predicted machining time. The impact of this is low energy consumption and good results. The best decision in the production process is a low production cost with good quality. CNC milling machines account for a large portion of the total

II. Material and Methods

1. Materials

The research used simulation and experimentation. The use of this simulation method is used in the machining process because of its ability to produce results that are close to the experimental process. The simulation program to generate machining time is carried out using Mastercam X5 software. This software serves to generate CNC program code. The software is used to set the machining speed parameters and toolpath motion strategy CNC machining process. In the CAM process, it can also simulate the machining time with the bracket design as shown in Figure 1, with dimensions 131 x 64 x 5 mm. The bracket material is 6061 aluminum with the composition in Table 1.

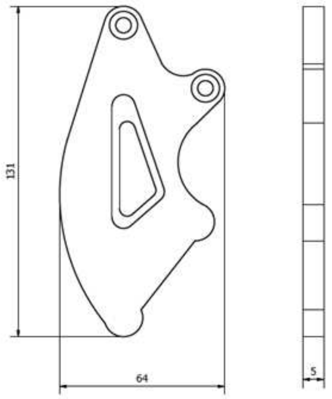

Figure 1. Aluminum bracket design

Table 1. Composition of 6061 Aluminum

Element	Si	Fe	Cu	Mn	Cr	Ni	Zn	Ti	Ga	V	Al
Chemical Composition %	0.74	0.6	0.28	0.11	1	0.17	0.013	0.07	0.022	0.009	REM.

Table 2. Aluminum characteristics

Characteristics	High-purity aluminum
Crystal structure	FCC
Density at 20°C (sat. 10^3kg/m^3)	2.698
Tensile strength (MPa)	690
Modulus of elasticity (GPa)	70.5
Modulus of rigidity (GPa)	26.0

2. Machining Process Parameters

Feed Rate

The relationship between the feed rate and the machining process time is directly proportional. The faster the feed rate, the faster the workpiece feeding process will shorten the machining process time. This parameter is very significant in several machining factors, including machining process time and workpiece surface roughness, with the relationship in Eq. (1).

$$Vf = N \times fz \times Z \qquad (1)$$

Where Vf is the feed rate (mm/min), N is the rotation speed (Rpm), fz is the feed rate per tooth (mm/tooth), and Z is the number of end mill cutting edges [18]-[20].

Cutting Speed

The relationship between cutting speed and cutting time is influenced by the feed rate. Cutting speed depends on the type of material used and affects the cutting results. To produce large cuts depending on the spindle rotation and feed rate. The more the workpiece is reduced so that it can affect the machining process time. This parameter is very significant in the machining process because it directly affects the stability of machining. The relationship between parameters is formulated by Eqs (2), (3), and (4).

$$Vc = \frac{\pi x d x n}{1000} \quad (2)$$

$$Vf = f \, x \, n \quad (3)$$

$$Tm = n \, x \, Vf \quad (4)$$

Where Vc is cutting speed (m/min), d is cutting tool diameter (mm), n is machine/workpiece rotation (rev/min - Rpm), π is constant value (3.14), f is feeding (feed/rev), and Tm is machining time (minutes) [18]-[20].

Depth of cut

The relationship between the depth of cut and the machining process time occurs due to the number of repetitions and the length of the feed path. The deeper the feed will reduce the number of passes made by the tool [18]-[20].

Energy Consumption

Energy consumption on the 3-axis CNC milling mini router machine, with the relationship between each feeding parameter and the power consumption in the machining process. When the machine moves, the energy required is read by the increase in the need for electric current flowing through the CNC machine. The relationship between the current and the power required to drive the machine is as in equation 5.

$$P = V \, x \, I \quad (5)$$

Where P is the power (watts), V is the voltage generated from the feeding process (volts), and I is the electric current generated from the feeding (ampere) [21].

After obtaining the power consumption, it will be associated with the machining process time. The relationship between power and energy consumption required in the production process is as in equation 6.

$$E = P \, x \, t \quad (6)$$

Where E is energy consumption (Watt-hour), P is power (watt), and T is machining process time (hour) [21].

Toolpath Strategy Motion

The toolpath motion in CNC milling is the feeding path of the cutting blade or tool during the machining process to form a workpiece. The tool moves according to the planned G-code design. In Mastercam X5 software, there are 8 variations of toolpath motion strategy (Figure 2), namely Zigzag, Constant Overlap Spiral, Parallel Spiral, Parallel Spiral Clean Corners, Morph Spiral, High Speed, One Way, and True Spiral. The toolpath strategy variations are coded TP1 through TP8 [3].

Feed rate parameters with values of 700 mm/min, 800 mm/min, 900 mm/min, and 1000 mm/min. The toolpath motion strategies used are Zigzag (TP1), Constant Overlap Spiral (TP2), Parallel Spiral (TP3), and Parallel Spiral Clean Corners (TP4). The parameter limit

Vol. 9, No. 1, July 2025, pp. 114-125

used is a tool with an HSS material diameter of 6 with 4 flutes. Cutting speed with a value of 152 m/min. Spindle speed with a value of 8067 Rpm. Depth of cut 0.5mm, Contour, and pocket 2 mm.

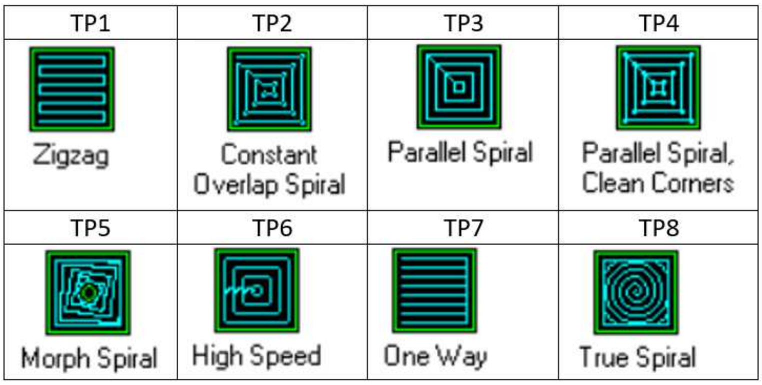

Fig. 2. Toolpath motion strategy

From the specified machining parameters, the results of the Machining Time simulation of each workpiece are obtained. The most optimal Machining Time is the smallest / smallest Machining Time data from various parameters that have been determined on the shape of the workpiece.

Measurement of Electrical Current and Voltage Values

For the measurement of electrical energy, assisted by using a clamp meter with type KT87N and made in China to measure voltage and electric current, it will be done like the procedure according to the Figure 3.

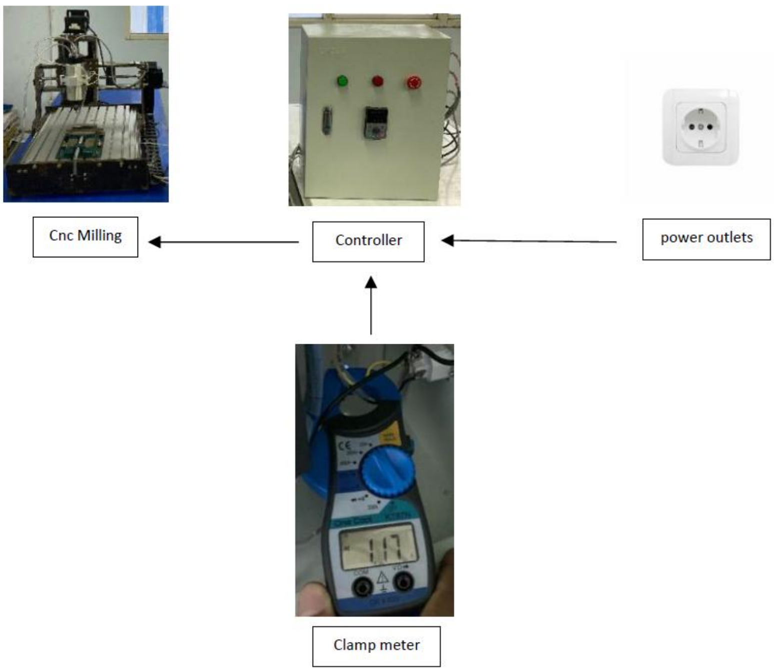

Fig. 3. Measurement procedure of electrical current and voltage values

III. Results and Discussions

The NC program is created in MastercamX5 software based on machining parameters and with a predetermined design. The process of making designs and programs is made in Mastercam X5 software according to the bracket design. In this software, simulation will also be carried out, and the machining process time will be obtained.

1. Zigzag Toolpath Motion

The first simulation was carried out using Zigzag toolpath motion. Zigzag motion is a movement with a tool pattern that moves forward and backward repeatedly. Figure 4 shows the Zigzag toolpath motion simulation performed in Mastercam X5 to determine the machining time for the bracket design. The resulting machining times for each feed rate parameter are summarized in Table 3.

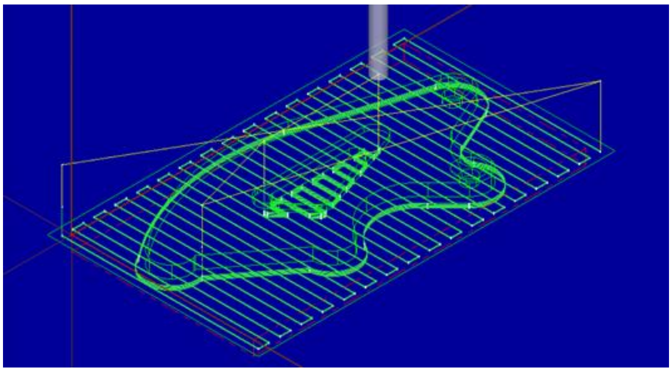

Fig. 4. Simulation of Zigzag toolpath motion

Table 3. Machining time of Zigzag toolpath motion

Toolpath Motion	Feed rate (mm/minute)	Machining time (minutes)			
		Facing	Contour	Pocket	Total
TP 1	700	20.48	3.40	2.28	26.56
	800	18.18	3.14	2.17	23.49
	900	16.20	2.53	2.9	21.23
	1000	14.47	2.37	2.2	19.26

Table 3 presents the machining times for the Zigzag toolpath motion at various feed rates. Based on these parameters, a graph illustrating total machining time is generated, as shown in Figure 4. The simulation results for the Zigzag toolpath motion (TP1) indicate that the shortest machining time occurs at a feed rate of 1000 mm/min (26.56 minutes), while the longest occurs at 700 mm/min (29.26 minutes).

2. Spiral Constant Overlap Toolpath Motion

The second simulation was performed using a Constant Overlap Spiral toolpath motion. The Constant Overlap Spiral motion is a spiral motion path pattern with a constant overlap distance. Figure 5 shows the simulation result of the Constant Overlap Spiral toolpath motion generated using Mastercam X5 software to determine the machining time for the bracket product design. The machining times for each feed rate parameter obtained from the simulation are presented in Table 4.

Table 4 presents the machining time for the Constant Overlap Spiral toolpath motion at each feed rate. Based on these feed rate parameters, a graph illustrating the total machining time is generated, as shown in Figure 5. Simulation results of machining time on the motion of the toolpath of Constant Overlap Spiral (TP2). The fastest machining time is the feed rate of 1000 mm/min, which is 20.2 minutes, and the longest is 700 mm/min, which is 28.16 minutes.

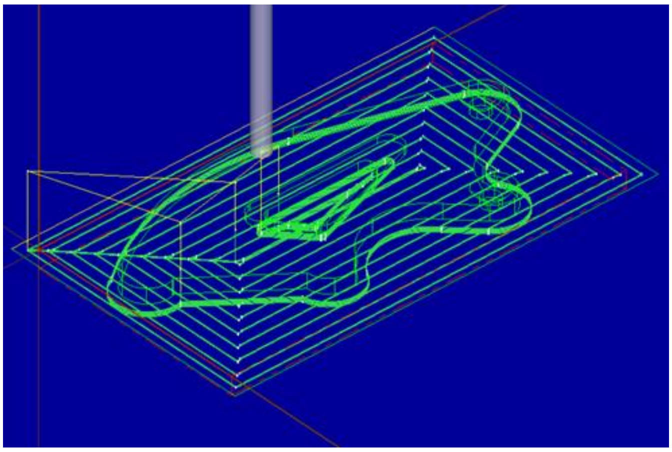

Fig. 5. Simulation of Constant Overlap Spiral toolpath motion

Table 4. Machining time of Constant Overlap Spiral toolpath motion

Toolpath motion	Feed rate (mm/minute)	Machining time (minutes)			
		Facing	Contour	Pocket	Total
TP 2	700	21.47	3.39	2.49	28.16
	800	19.9	3.13	2.35	24.57
	900	17.6	2.53	2.25	22.23
	1000	15.27	2.36	2.16	20.20

3. Parallel Spiral Toolpath Motion

The third simulation is performed using the Parallel Spiral toolpath motion. The Parallel Spiral motion is a motion path pattern by combines parallel motion in parallel and spiral motion in a circular distance. Figure 6 shows the result of the simulation of Parallel Spiral toolpath motion from Mastercam X5 software to obtain the machining process time of the bracket product design to produce a bracket product. The machining process time of each parameter of the feed rate obtained from the simulation results will be processed as shown in Table 5.

Table 5 presents the machining time for the Parallel Spiral toolpath motion at various feed rates. Based on these parameters, a graph illustrating the total machining time is generated, as shown in Figure 6. The simulation results for the Parallel Spiral toolpath motion (TP3) indicate that the shortest machining time occurs at a feed rate of 1000 mm/min (19.5 minutes), while the longest is at 700 mm/min (27.33 minutes).

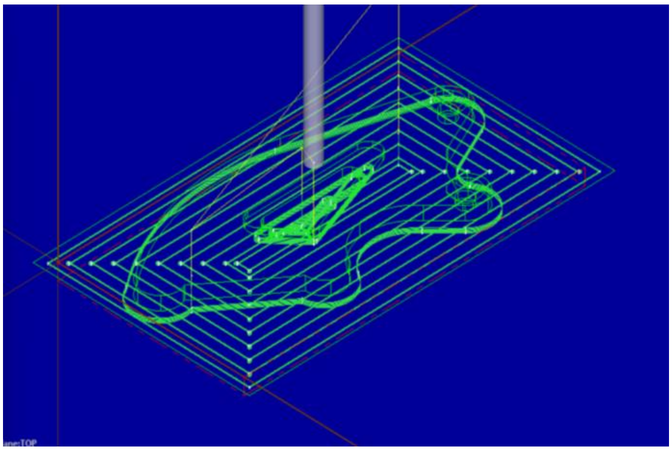

Fig. 6. Simulation of Parallel Spiral toolpath motion

Table 5. Machining time of Parallel Spiral toolpath motion

Toolpath Motion	Feed rate (mm/minute)	Machining time (minutes)			
		Facing	Contour	Pocket	Total
TP 3	700	21.20	3.40	2.33	27.33
	800	18.45	3.14	2.21	24.20
	900	16.44	2.53	2.12	21.50
	1000	15.8	2.37	2.5	19.50

4. Parallel Spiral Clean Corners Toolpath Motion

The fourth simulation is performed using Toolpath motion Parallel Spiral Clean Corners. The Parallel Spiral Clean Corners motion is the path pattern of the Parallel Spiral with additional motion at the corners.

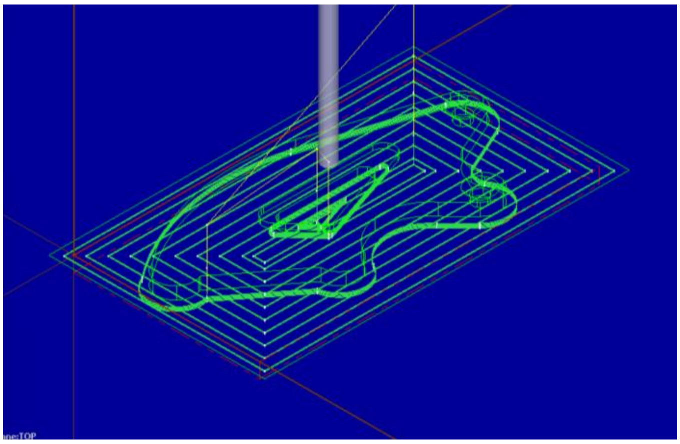

Fig. 7. Simulation of Parallel Spiral Clean Corners toolpath motion

Figure 7 shows the simulation result of the Parallel Spiral Clean Corners toolpath motion, generated using Mastercam X5 software, to determine the machining time for the bracket product design. The machining times for each feed rate parameter obtained from the simulation are summarized in Table 6.

Table 6. Machining time of Parallel Spiral Clean Corners toolpath motion

Toolpath Motion	Feed rate (mm/minute)	Machining time (minutes)			
		Facing	Contour	Pocket	Total
TP 4	700	22.1	3.40	3.26	29.6
	800	19.20	3.14	3.8	25.42
	900	17.16	2.53	2.54	23.3
	1000	15.36	2.37	2.43	20.56

Table 6 presents the machining time for the Parallel Spiral Clean Corners toolpath motion at various feed rates. Based on these parameters, a graph of the total machining time is generated, as shown in Figure 7. The simulation results for the Parallel Spiral Clean Corners toolpath (TP4) indicate that the shortest machining time is achieved at a feed rate of 1000 mm/min (20.56 minutes), while the longest occurs at 700 mm/min (29.6 minutes). After obtaining the machining time for each toolpath motion (in minutes), the values are converted into hours. To determine the required energy consumption, experiments are conducted to measure electrical power at each feed rate parameter. The resulting data are presented in Table 7.

Table 7. Energy consumption for each parameter

Feed Rate (mm/minute)	Toolpath Motion	Time Machining (Second)	Current (Ampere)	Energy Consumption (Kilojoule)
700	Zigzag	1593.6	1.17	410.192
	Constant overlap spiral	1689.6	1.17	434.903
	Parallel Spiral	1639.8	1.17	422.084
	Parallel Spiral Clean Corners	1776	1.17	457.142
800	Zigzag	1409.4	1.19	368.980
	Constant overlap spiral	1474.2	1.19	385.945
	Parallel Spiral	1452	1.19	380.133
	Parallel Spiral Clean Corners	1525.2	1.19	399.297
900	Zigzag	1273.8	1.2	336.283
	Constant overlap spiral	1333.8	1.2	352.123
	Parallel Spiral	1290	1.2	340.560
	Parallel Spiral Clean Corners	1398	1.2	369.072
1000	Zigzag	1155.6	1.21	307.620
	Constant overlap spiral	1212	1.21	322.634
	Parallel Spiral	1170	1.21	311.454
	Parallel Spiral Clean Corners	1233.6	1.21	328.384

Based on the energy consumption data, it can be seen that in each parameter feed rate of 700, 800, 900, and 1000 mm/min, the largest energy consumption is obtained in the Parallel Spiral Clean Corners tool motion strategy with a feed rate of 700 mm/min with a value of 457.142 Kilojoules. In accordance with the machining process time on these parameters, which results in the longest machining process time. The smallest energy consumption is obtained from the Zigzag tool motion strategy with a feed rate of 307.620 Kilojoules. In accordance with the machining process time on these parameters, which results in the fastest machining process time. Based on the data, the Zigzag toolpath motion produces the smallest energy consumption due to the non-repetitive feeding motion system and sequentially in both directions, namely forward and backward, and moves continuously so as to reduce machining time to the data obtained that the Zigzag toolpath motion produces the fastest time from the data above. As for the Parallel Spiral Clean Corners toolpath motion, it produces the largest energy consumption due to the feeding movement system that rotates from the inside out different from the Zigzag, which only goes back and forth. There is also an additional movement at each corner that will increase the length of the feeding path, which will make the feeding process longer, therefore, the Parallel Spiral Clean Corners toolpath motion will produce the longest time from the data above [1],[22],[23]. Therefore, the selection of the feed rate is very influential because the higher the feed rate, the more material is cut and the faster the tool moves, which will affect the energy consumption in the machining process.

IV. Conclusions

In this research, 4 toolpath motion strategies, namely Zigzag, Constant overlap spiral, Parallel Spiral, and Parallel Spiral Clean Corners, and the parameters of feed rate are 700 mm/min, 800 mm/min, 900 mm/min, and 1000 mm/min, have been evaluated. Based on the data analysis, it can be concluded that the selection of toolpath motion and feed rate is critical, as it directly affects the machining process time of the CNC milling machine, which in turn influences energy consumption during the machining process. The results show that a feed rate of 1000 mm/min with a Zigzag toolpath motion produces the lowest energy consumption, at 307.620 kilojoules. In contrast, a feed rate of 700 mm/min with a Parallel Spiral Clean Corners toolpath motion results in the highest energy consumption, at 457.142 kilojoules. Therefore, the selection of feeding parameters, especially toolpath motion and feed rate in the CNC milling machining process is very influential in the machining process time and the use of electrical energy so that it will affect the electrical energy consumption in the machining process which will have an impact on production costs, with the selection of the right machining parameters will be able to minimize production costs. The results of this research are expected to benefit the industrial sector, particularly in manufacturing and energy industries, by enhancing productivity and cost efficiency. This can be achieved through the optimization of machining parameters, such as machining speed and toolpath strategy, to improve energy efficiency and reduce production costs. Future research should explore a broader range of parameters to optimize energy efficiency in more complex systems and consider integrating advanced technologies, such as the Internet of Things (IoT), to obtain more real-time and accurate data.

References

[1] A. Pajaziti, O. Tafilaj, A. Gjelaj, and B. Berisha, "Optimization of toolpath planning and CNC machine performance in time-efficient machining," *Machines*, vol. 13, no. 1, pp. 1–20, Jan. 2025, doi: 10.3390/machines13010065.

[2] B. Kasim, A. Yunus, I. Yusuf, Mawardi, and Darmein, "Optimization of CNC machining parameters to improve surface roughness quality of the AL6061 material using the Taguchi method," *Jurnal Polimesin*, vol. 21, no. 4, pp. 408–413, 2023, [Online]. Available: http://e-jurnal.pnl.ac.id/polimesin

[3] W. Sumbodo, Kriswanto, Murdani, I. Suwanda, and T.S. Allam, "Optimization of CNC milling machining time through variation of machine parameters and toolpath strategy in various cross-sectional shape on tool steels and die steels materials," in *Proceedings of the 7th Engineering International Conference on Education*, Scitepress, Apr. 2020, pp. 84–92. doi: 10.5220/0009006800840092.

[4] A. Ambroziak, M.T. Solarczyk, and A. Biegus, "Numerical and analytical investigation of alumunium bracket strengthening," *Archives of Civil Engineering*, vol. 64, no. 2, pp. 37–54, 2018, doi: 10.2478/ace-2018-0015.

[5] R. Raharjo, T.D. Widodo, and R. Bintarto, "Desain manufaktur bracket alumunium," *Jurnal Rekayasa Mesin*, vol. 9, no. 2, pp. 119–125, 2018, doi: 10.21776/ub.jrm.2018.009.02.8.

[6] W.D. Lestari, A.T. Danaryanto, A. Nugroho, R. Ismail, J. Jamari, and A.P. Bayuseno, "Wear property of machined Ultra High Molecular Weight Polyethylene (UHMWPE) acetabular liner product with CNC milling," *Journal of Mechanical Engineering Science and Technology (JMEST)*, vol. 5, no. 2, pp. 110–122, 2021, doi: 10.17977/um016v5i22021p110.

[7] C. Camposeco-Negrete and J. de Dios Calderón-Nájera, "Optimization of energy consumption and surface roughness in slot milling of AISI 6061 T6 using the Response Surface Method," *International Journal of Advanced Manufacturing Technology*, vol. 103, no. 9–12, pp. 4063–4069, Aug. 2019, doi: 10.1007/s00170-019-03848-2.

[8] R. Prasetya, A. Andoko, S. Suprayitno, R. Wulandari, P. Trihutomo, K. Mishima *et al.*, "Simulation of the performance of Kevlar impregnated shear thickening fluid ballistic test results," *Journal of Mechanical Engineering Science and Technology (JMEST)*, vol. 8, no. 1, pp. 54–70, May 2024, doi: 10.17977/um016v8i12024p054.

[9] Y. Novrialdy, K. Arwizet, A. Yufrizal, and F. Prasetya, "Pengaruh variasi feed rate terhadap kekasaran permukaan polyethylene menggunakan mesin CNC milling," *Jurnal Vokasi Mekanika*, vol. 3, no. 2, pp. 25–33, 2021, [Online]. Available: http://vomek.ppj.unp.ac.id

[10] H.B. Harja, E. Suherlan, N. Rusmana, and D.K. Nugraha, "Experimental study of geometric error of CNC turning machine tools based on ISO 13041-6," *Jurnal Polimesin*, vol. 21, no. 4, pp. 395–402, 2023, [Online]. Available: http://e-jurnal.pnl.ac.id/polimesin

[11] R. Prajapati, A. Rajurkar, and V. Chaudhary, "Tool path optimization of contouring operation and machining strategies for turbo machinery blades," *International Journal of Engineering Trends and Technology (IJETT)*, vol. 4, no. 5, pp. 1731–1737, 2013, [Online]. Available: http://www.ijettjournal.org

[12] K.A. Shamsuddin, A.R. Ab-Kadir, and M.H. Osman, "A Comparison of milling cutting path strategies for thin-walled aluminium alloys fabrication," *The International Journal Of Engineering And Science (IJES)*, vol. 2, no. 3, pp. 01–08, 2013, [Online]. Available: www.theijes.com

[13] A. Indaka and B. Wahyudi, "Optimization of CNC milling parameters using The Response Surface Method for Aluminum 6061," *Jurnal Polimesin*, vol. 22, no. 3, 2024, [Online]. Available: http://e-jurnal.pnl.ac.id/polimesin

[14] G. Musca, A. Mihalache, and L. Tabacaru, "Increase productivity and cost optimization in CNC manufacturing," in *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, Dec. 2016, pp. 1–6. doi: 10.1088/1757-899X/161/1/012019.

[15] S. Daneshmand, M. Mirabdolhosayni, and C. Aghanajafi, “Sifting through the optimal strategies of time-based tools path machining in software CAD-CAM,” *Middle East J Sci Res*, vol. 13, no. 7, pp. 844–849, 2013, doi: 10.5829/idosi.mejsr.2013.13.7.2658.

[16] R.N. Amrullah, S. Hadi, and M.A. Rizza, “Simulation-based methodology to investigate the impact of material type and compressive speed variation on effective strain rate and springback,” *Journal of Mechanical Engineering Science and Technology (JMEST)*, vol. 8, no. 2, p. 229, Sep. 2024, doi: 10.17977/um016v8i22024p229.

[17] H.S. Haryadi, P. Moengin, and P. Astuti, “Designing system production to increase production capacity using simulation methods,” *Jurnal Teknik Industri*, vol. 13, no. 3, pp. 223–230, 2023, Accessed: Apr. 19, 2025. [Online]. Available: https://e-journal.trisakti.ac.id/index.php/tekin/article/view/19144

[18] G. Ramavat, O. Beedalannagari, S. Patil, F. Romero, F. Ajila, A. Singhal, *et al.*, “A Comprehensive review on optimization of process variables for CNC milling,” *Nano World Journal*, vol. 9, no. 3, pp. 786–791, Nov. 2023, doi: 10.17756/nwj.2023-s3-138.

[19] H. Shagwira, T.O. Mbuya, F.M. Mwema, M. Herzog, and E.T. Akinlabi, “Taguchi optimization of surface roughness and material removal rate in cnc milling of polypropylene + 5wt.% quarry dust composites,” in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, Apr. 2021, pp. 1–9. doi: 10.1088/1757-899x/1107/1/012040.

[20] R. Suryadi, D. Riana, and Kangen, “Pengaruh parameter proses CNC milling terhadap surface roughness dan toleransi bidang pada inlet outer valve,” *Jurnal Teknik Mesin*, vol. 6, no. 2, pp. 53–62, 2022, Accessed: Apr. 19, 2025. [Online]. Available: http://repository.iti.ac.id/handle/123456789/2096

[21] L.D. Saputra and E. Yudiyanto, “Analisis performa mesin CNC milling mini 3 sumbu terhadap akurasi gerak pemotongan,” *Journal of Mechanical Engineering*, vol. 1, no. 3, pp. 1–11, 2024, [Online]. Available: https://journal.pubmedia.id/index.php/jme

[22] I. Sztankovics, “The analytical and experimental analysis of the machined surface roughness in high-feed tangential turning,” *MDPI (Eng)*, vol. 5, pp. 1768–1784, Aug. 2024, doi: 10.3390/eng5030093.

[23] W. Sumbodo, Kriswanto, and J. Jamari, “Simulation and optimization of machining time during milling AISI P20 steel,” in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Mar. 2021, pp. 1–8. doi: 10.1088/1755-1315/700/1/012002.