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Energy Efficiency Analyses of Toolpaths in a Pocket Milling Process

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ABSTRACT

This paper presents an approach to analytically determine the most energy efficient toolpath strategy in mechanical machining. This was achieved by evaluating the electrical energy requirement of the NC codes generated for the zag, zigzag, and rectangular contour toolpath strategies. The analytical method was validated by performing pocket milling on AISI 1018 steel with the considered toolpaths using a 3-axis Takisawa Mac-V3 milling machine. The rectangular contour toolpath was the most efficient in terms of the electrical energy demand of the feed axes and cycle time. Pocket milling with the zigzag toolpath strategy resulted in higher electrical energy demand of the feed axes and cycle time by 2% due to acceleration and deceleration characteristics of the machine tool feed axes execution at corners of the toolpath strategy adopted. Also, the electrical energy demand of the feed axes and cycle time for the zag toolpath were higher by 14% and 8%, respectively, due to the number of tool retracts as a result of the executed toolpath strategy. The experimental validation results showed good agreement with the analytical approach presented in this study. It can be deduced that for sustainable machining, the rectangular contour toolpath should be adopted since it has less tool retractions irrespective of the toolpath strategy adopted for machining. This could further enhance the selection of optimum green parameters by shop floor process engineers for sustainable manufacture of products.

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1. INTRODUCTION[1]

The International Energy Outlook (IEO2013) projected the global industrial energy demand to increase between 2010 and 2040 from 0.06 quadrillion kWh to 0.09 quadrillion kWh, which indicates an average increase of 1.4 % per annum [1]. In 2011, the United States Energy Information Agency (EIA) reported that the industrial sector consumed 0.08 quadrillion kWh [2], being 51% of the total global energy demand (0.16 quadrillion kWh) [3], while the value decreased to 0.0003 quadrillion kWh in UK [4]. The energy consumed accounted for 457.5 million tonnes (Mt) of CO_2 equivalent emission for 2011 in UK. This further affirms the contributions of the manufacturing sector to increase the carbon footprint and the environmental impacts of such processes. Therefore, the use of sustainable technologies and best available practices (BAP) could provide significant energy saving and CO_2 reduction in the manufacturing sector [5].

Mechanical machining is one of the widely used technologies in the manufacturing sector due to its versatility and accuracy in the fabrication of products. Machine tools possess high intensity of electrical energy demand [6, 7]. This electrical power demand fluctuates based on operating states of the machine tool. For example, Edem and Mativenga [8] proposed a power-time profile for the power consumed when undertaking peripheral milling of AISI 1018 steel on a 3-axis Takisawa Mac-V3 milling machine.

In a bid to reduce the constant electrical energy demand of machine tools, few researchers have proposed different methods and suggested specific recommendations. For example, Diaz et al. [9] utilised the kinetic energy recovery system (KERS) on the Mori Seiki NV1500DCG to achieve power savings of up to 25% when compared with the same machine tool without KERS. Li and Kara [10] suggested that it is possible to achieve power reduction at the design stages

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of machine tool components, and proposed: 1) switching off the machines during long idle periods; 2) attaining of energy saving mode during idle periods through constant time breaks; and 3) the provision of the Human Machine Interface (HMI) device to trigger manual operations on the machines for energy reduction strategies. Mori et al. [11] developed a new acceleration and deceleration control method for reducing energy consumption by synchronising spindle acceleration with feed system. Kroll et al. [12] reported that weight reduction of machine components tends to decrease the acceleration time and hence reduces the processing time. This is because lower gravitational and inertia forces are created and the overall energy for moving masses is reduced. Edem and Mativenga [13] suggested that the design and material choice of the vice to be mounted on the machine table with regards to its weight should be considered in order to reduce energy consumption.

Other researchers also proposed methods of minimising the electrical energy demand in machining processes. Rangarajan and Dornfeld [14] developed a method for reducing feedrate losses due to abrupt toolpath changes as well as determining the best feedrate for machining a segment. They reported that 2 – 4% reduction in cycle time may be achieved which could result in more than 10 – 20% of energy savings. Balogun et al. [15] used the relationship between the cutter swept angle and specific ploughing energy to develop an optimised model for determining minimum ploughing effect in a milling process. The authors reported that minimum ploughing effect could be achieved at a cutter swept angle value of 39.74º when machining with a tool that has an edge radius of 60 µm. Yan and Li [16] utilised the grey relational analysis and the response surface methodology to determine the optimal cutting parameters (including feedrate, spindle speed, depth of cut, and width of cut) that would enhance the identification of the most efficient cutting parameter for reduced cutting energy demand, improved surface finish, and increased material removal rate for a milling process. It was observed that machining at low spindle speeds results in minimal energy demand. Al-Ghamdi and Iqbal [17] investigated the impacts of feedrates, cutting speeds, minimum quantity lubrication on tool life, machining forces, productivity, process costs, and specific energy consumption. The authors reported that energy efficiency can be correlated with the high speed machine tool. Camposeco-Negrete [18] studied the effects of the depth of cut, feedrate, and cutting speed on the energy required in turning AISI 1018 steel and reported that higher feedrate, minimum depth of cut, and minimum cutting speed combination results in lower energy demand. Balogun and Edem [19] investigated the impact of swept angle optimization and their influence on the specific cutting energy in milling AISI 1045 steel alloy by varying the step over at different feedrate values, in order to determine the optimization criterion for machining. It was observed that an optimum swept angle of 31.8° was appropriate in the elimination of ploughing effect and reducing the specific cutting energy to an optimised minimum value. Edem and Mativenga [20] reported that the energy intensity in mechanical machining could be significantly reduced by selecting toolpaths with longer linear path segments as a result of the minimal constraints imposed by acceleration and deceleration of the feed drive which enables the maximum feedrate to be reached.

1. 1. Toolpath Strategies

Toolpaths guide the cutter through the machined region and enable the removal of material to a fixed depth from some arbitrary closed boundary on a flat workpiece surface. This process is called pocketing and the shape produced is called pocket [21]. In milling, two types of toolpath strategies are commonly utilised namely the direction-parallel toolpaths (zag, zigzag) and the contour parallel toolpaths (rectangular contour spiral and true spiral).The zag toolpath strategy requires the tool to move in a parallel direction while machining the pocket, then retracts at the end of the path, steps over in a fixed distance, and returns to the start point to continue with the machining process. However, the tool movement during the zigzag strategy is in the to-and-fro directions with regards to the x-y plane of the machine table, resulting in up and down milling processes due to the change in direction of the tool movement. The contour-parallel toolpath consists of a series of contours that are parallel to the boundary or geometry on the flat workpiece [22]. Mechanical machining of parts with efficient toolpath strategies could lead to minimum processing time, improved surface finish [23, 24], higher tool life [25], and minimum energy demand [8].

Analytical methods were also adopted to determine optimal toolpath strategies in milling. For example, Park and Choi [26] proposed toolpath linking algorithms to determine the optimal toolpath strategy with minimum number of tool retractions and the number of elements for the zag and zigzag toolpaths. The authors utilised the concept of monotone chain and the plane-sweep paradigm to calculate the toolpath elements. Kim and Choi [27] developed a machining time model which incorporates the impacts of acceleration and deceleration of the CNC machine in order to determine the most efficient toolpath strategy. Although from their results it could be deduced that the smooth zig-zag toolpath was the most efficient toolpath strategy irrespective of the feedrate and path interval, the feed axes energy model which incorporates the weights moved by the feed drive was not incorporated into the evaluation of the energy efficient toolpath strategy. Toh [25] studied the influence of rectangular contour offset, zigzag, and zag toolpath strategies on machining time without due consideration on the electrical energy demand of toolpaths. El-Midany et al. [22] proposed a feedrate machining time model for normal zig-zag, smooth zig-zag, normal spiral, smooth spiral and fishtail toolpaths. It was concluded that the most efficient toolpath strategy depends on the part geometry, the CNC machine characteristics, and the cutting conditions. Analytical estimation method was also adopted to determine the power demand of two axes feed motors based on NC codes by evaluating the actual feedrate for each axes [28]. The power demand of the feed axes was estimated from the angle of orientation and their corresponding axis feedrates. However, the study did not investigate optimum toolpath strategies for energy consumption reduction. Moreover, the effects of the weights of the feed axes, workpiece and machine vice were not considered in the analytical power estimation. Edem and Mativenga [8] undertook a systematic study of work holding device and toolpath orientation, as well as toolpath strategies for milling operations. They concluded that machining toolpaths aligned to the lighter axis reduced the electrical energy demand and surface roughness by 29 and 50%, respectively. Nevertheless, this work did not utilise the power demand model of the feed axes to estimate the feed axes' power demand of toolpaths.

Altintas et al. [29] investigated the effect of toolpath strategies on the electrical energy demand and total processing time. Six toolpath strategies (i.e. follow path, follow periphery, profile, zig, zigzag, and zig with contour) were engaged to mill a rectangular open pocket standard for exchange of product (STEP) feature. It was reported that the zigzag toolpath strategy resulted in minimum energy demand while the zig with contour toolpath resulted in high energy demand. Li et al. [30] theoretically analysed the optimal machining toolpath strategies in order to improve energy efficiency of CNC machining. End milling was performed on a CNC machining centre HAAS-VF5 with the zigzag in x-axis direction, zigzag in y-axis direction, zigzag in 45^o, contour offset and spiral toolpath strategies. Results showed that air cutting time was higher when utilising the spiral toolpath due to the number of tool retracts; thereby, resulting in higher energy demand. The air cutting time was minimal for zigzag in x-axis direction. Nevertheless, the importance of weights moved by the feed drive was not highlighted in their theoretical analyses. Recently, Edem et al. [31] investigated the impacts of toolpath strategies and machine tool axes configurations on electrical energy demand in mechanical machining. This was achieved by performing pocket milling of AISI 1018 steel with the zag, zigzag, and rectangular contour toolpaths on two 3-axis CNC milling machines. Results showed that the electrical energy efficiency of toolpaths machining strategy varied from one CNC milling machine to another one due to their structural configurations.

The literature has provided insight into few analytical approaches for determining efficient toolpath strategies based on the machining time. However, the proposed models did not determine the optimal toolpath strategy in terms of electrical energy demand and processing time and at the same time did not consider the feed axes energy demand model which incorporates the weights of the feed axes, workpiece and machine vice. Since numerical control (NC) codes (i.e. G, M, S, and F-codes) control the functional performance of NC machines, it is therefore important to determine the optimal toolpath strategy that incorporates the generic feed axes energy demand model found in literature to evaluate the feed energy demand of toolpaths from the generated NC codes.

1. 2. Research Aim The aim of this work is to investigate the energy demand of machining toolpath strategies in a milling process. This was to determine the green and the most efficient toolpath strategy. In lieu of this, pocket milling on AISI 1018 steel with the zag, zigzag, and rectangular contour toolpaths were conducted on a 3-axis CNC milling machine in order to validate the proposed analytical approach for optimal toolpath prediction. The knowledge obtained in this study would aid process planners in selecting optimum toolpath strategy for improved energy efficiency in mechanical machining.

2. ELECTRICAL ENERGY DEMAND ESTIMATION OF TOOLPATH STRATEGIES WITH REGARDS TO FEED AXES DIRECTIONS

Energy saving measures in toolpath strategies could be achieved by using appropriate models to predict the energy required to machine a product based on numerical control (NC) codes. The energy efficiency of toolpaths may be affected by the structural configuration of the feed axes due to the difference in weights moved by each axis [32]. This would be ascertained by adopting the power demand model for feed axes proposed by Edem and Mativenga [13] and presented in Equation 1 to estimate the feed axes' power demand of toolpaths.

$$\mathrm{P_{f-feed} = P_0 + (a_i W_i v_{f_i} + b_i W_i) + F_f v_f} \quad (1)$$

where $P_{f\text{-}feed}$ is the power of the feed axes in the specified axes direction in W, P_0 is the baseline power demand at idle state, W_i is the weight of the specified axis, workpiece, and machine vice in N, a_i and b_i are constants in the x- and y- axes directions, v_{fi} is the rapid feed or table feedrate in the specified axis direction in m/s, and F_f is the feed force in N.

The machining toolpath's cutting length and direction influence the material removal cycle time. The cycle time and direction of the cutting tool relative to the workpiece can be evaluated by taking into account the acceleration and deceleration time of the feed axes movement [33]. The time required to accelerate and decelerate the feed drives depends on the maximum feedrate and axis acceleration to be attained by the drive and the controller parameters of the machine tool.

Two types of feed profiles are normally used for the feed axes movement. These include the trapezoidal feed profile and the triangular feed profile presented in Figures 1(a) and 1(b).

The trapezoidal feed profile in Figure 1a shows that the distance travelled by the feed axes or cutter is long enough to allow acceleration, stabilisation and deceleration of the feed axes, thereby making it possible for the required feedrate to be reached at any instance of the machining operation. In the case of the triangular axis movement in Figure 1b, the specified feedrate cannot be reached due to the fact that the feed axis or cutter travel distance is shorter than the time required for the drive to accelerate, stabilise and decelerate [32]. Therefore, based on Figures 1a and 1b, the time required to run an NC block can be estimated for trapezoidal feed profile as shown in Equation 2; while Equation 3 can be adopted for the triangular feed profile depending on the length of the toolpath segment.

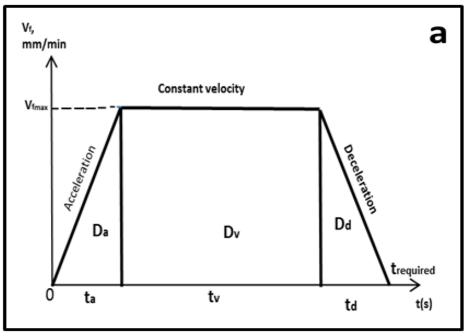


Figure 1(a). Acceleration and deceleration phase of the feed drive as it undergoes trapezoidal movements

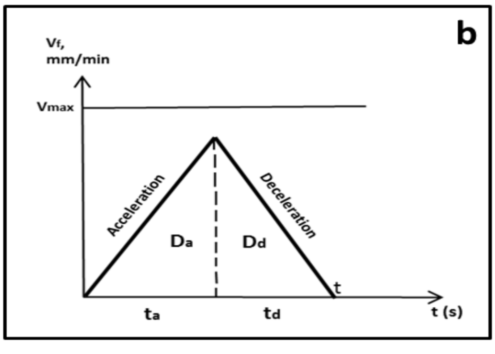


Figure 1(b). Acceleration and deceleration phase of the feed drive as it undergoes triangular axes movements

$$\boldsymbol{t_{required}} = \boldsymbol{2t_a} + \frac{\boldsymbol{D-2D_a}}{\boldsymbol{v_f}} \qquad (\boldsymbol{D \geq 2D_a}) \tag{2}$$

$$\boldsymbol{t_{required}} = \sqrt{\frac{\boldsymbol{2t_aD}}{\boldsymbol{v_f}}} \qquad (\boldsymbol{D} < 2\boldsymbol{D_a}) \tag{3}$$

where t_a is the acceleration time in *s*, D is the total travel distance in *mm*, D_a is the distance moved by the tool or axis at the acceleration time t_a, and v_f is the feedrate in *mm/min*

The electrical energy demand of the feed axes could be estimated from Equation 1 (i.e. feed axes power) and from either Equation 2 or 3 (cycle time) depending on the activated program feedrate or rapid feedrate. Therefore, modifying Equation 1 and incorporating the cycle time based on the feed profile, Equations 4 and 5 can be deduced as proposed by Edem and Mativenga [13].

$$\mathrm{E_f} = \mathrm{E_{f-feed}} + \mathrm{E_{r-feed\,(approach)}} + \mathrm{E_{r-feed\,(retract)}} \tag{4}$$

$$\mathrm{E_f} = \left(\mathrm{P_0} + \left(\mathrm{a_iW_iv_{f_i}} + \mathrm{b_iW_i}\right) + \mathrm{F_fv_{f_i}}\right)\mathrm{t_{cy}} + \left(6502\mathrm{v_{f_a}} + 2838.3 + \mathrm{F_fv_{f_a}}\right)\mathrm{t_{cy}} + (8540\mathrm{v_{f_a}} + 2852 + \mathrm{F_fv_{f_i}})\mathrm{t_{cy}} \tag{5}$$

where E_f is the total electrical energy demand of the feed axes in *J*, $E_{f\text{-}feed}$ is the energy demand of the feed axes in specified axes directions and feedrates in *J*, $E_{r\text{-}feed(approach)}$ is the energy demand of the feed axes during tool approach at rapid or specified feedrate in *J*, $E_{r\text{-}feed(retract)}$ is the energy demand of the feed axes during tool retract at rapid or specified feedrate in *J*, v_{fa} is the specified or rapid feedrate for tool approach or tool retract in z-axis direction, t_{cy} is the cycle time in *s* while P_0, W_i, a_i and b_i, v_{fi} and F_f still retain their usual meanings. It should be noted that during rapid traversing mode or tool retract, $F_f = 0$.

For the purpose of evaluating the theoretical total energy demand of the feed axes E_f, NC codes from different toolpath strategies (zag, zigzag, and rectangular contour) were generated with the hyper mill CAM software. Figure 2 shows the sample workpiece with different toolpath strategies. The pocket length for zag, zigzag, and rectangular contour offset was 122 *mm* while the width was 54 *mm*.

Table 1 presents the NC codes for one of the toolpath strategies (zigzag in x-direction), as well as the feed axis energy and cycle time evaluated using Equations 4 and 5, respectively. The basic machine power demand for Takisawa was measured as 2763.18 W. This value was incorporated into Equation 5 as P_0 while the vector coordinates of the corresponding NC codes were evaluated and presented in Table 1.

Table 2 presents results for the feed axes energy demand, total cycle time to run the NC program for each toolpath, and the time required for rapid move, tool retract and tool approach (otherwise called non-cutting energy).

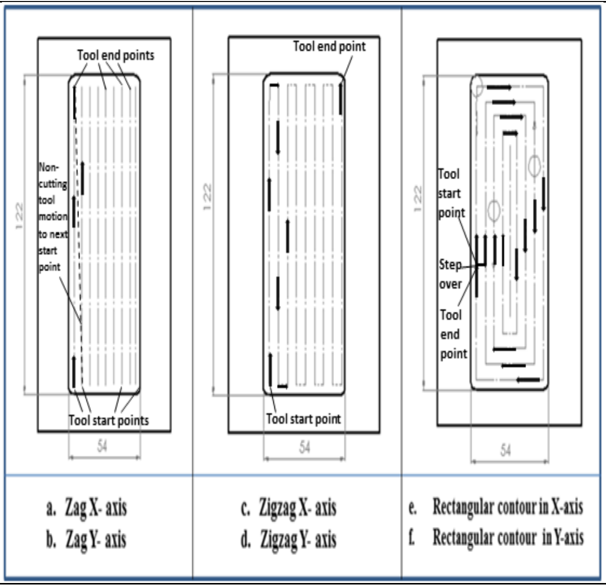
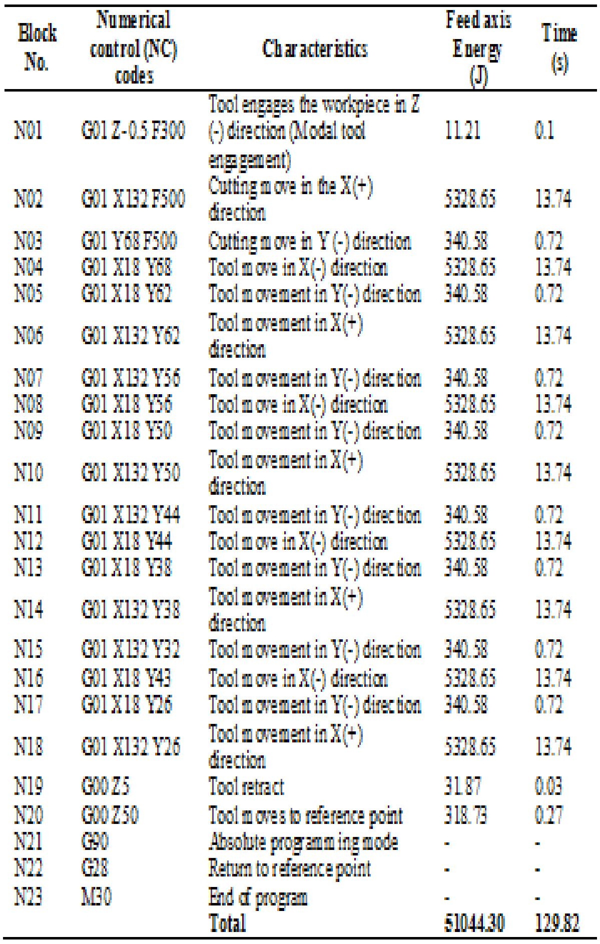


Figure 2. CAM toolpath showing different toolpath strategies

TABLE 1. NC code sequences for zigzag toolpath in x-axis direction



Block No.	Numerical control (NC) codes	Characteristics	Feed axis Energy (J)	Time (s)
N01	G01 Z-0.5 F300	Tool engages the workpiece in Z (-) direction (Modal tool engagement)	11.21	0.1
N02	G01 X132 F500	Cutting move in the X(+) direction	5328.65	13.74
N03	G01 Y68 F500	Cutting move in Y (-) direction	340.58	0.72
N04	G01 X18 Y68	Tool move in X(-) direction	5328.65	13.74
N05	G01 X18 Y62	Tool movement in Y(-) direction	340.58	0.72
N06	G01 X132 Y62	Tool movement in X(+) direction	5328.65	13.74
N07	G01 X132 Y56	Tool movement in Y(-) direction	340.58	0.72
N08	G01 X18 Y56	Tool move in X(-) direction	5328.65	13.74
N09	G01 X18 Y50	Tool movement in Y(-) direction	340.58	0.72
N10	G01 X132 Y50	Tool movement in X(+) direction	5328.65	13.74
N11	G01 X132 Y44	Tool movement in Y(-) direction	340.58	0.72
N12	G01 X18 Y44	Tool move in X(-) direction	5328.65	13.74
N13	G01 X18 Y38	Tool movement in Y(-) direction	340.58	0.72
N14	G01 X132 Y38	Tool movement in X(+) direction	5328.65	13.74
N15	G01 X132 Y32	Tool movement in Y(-) direction	340.58	0.72
N16	G01 X18 Y43	Tool move in X(-) direction	5328.65	13.74
N17	G01 X18 Y26	Tool movement in Y(-) direction	340.58	0.72
N18	G01 X132 Y26	Tool movement in X(+) direction	5328.65	13.74
N19	G00 Z5	Tool retract	31.87	0.03
N20	G00 Z50	Tool moves to reference point	318.73	0.27
N21	G90	Absolute programming mode	-	-
N22	G28	Return to reference point	-	-
N23	M30	End of program	-	-
		Total	51044.30	129.82

From Table 2, it can be observed that the zag toolpath strategy had the longest cycle time due to the number of tool retracts that the toolpath strategy underwent. This means that 10% of the total cycle time was attributable to the non-cutting tool movements (i.e. time required by the tool to rapidly move to the next cutting start point, tool retract and tool approach); thereby, increasing the cycle time. However, the other toolpath strategies (zigzag and rectangular contour) had assumed zero tool retracts. Figure 3 shows variation of predicted theoretical feed axes energy demand based on different toolpath strategies.

From Figure 3, it is observed that the theoretical feed axis energy demand in the y-axis direction is higher than the x-axis by 29, 19, and 11% for the zag, zigzag, and rectangular contour toolpaths, respectively. This is because the x-axis weighs less than the y-axis; thereby resulting in more weights being moved in the y-axis direction. Figure 3 also shows that the rectangular contour toolpath is the most efficient in terms of energy demand and processing time. The reason may be due to longer cutting length of the toolpath before the next cutting pass.

Considering the zigzag toolpath, the short links between one cutting pass and the next increased the processing time and feed energy demand by 2% due to acceleration and deceleration of the machine tool at corners. The feed energy and the processing time for the zag toolpath were higher by 14 and 8%, respectively than that of the rectangular contour toolpath. This was as a result of the number of tool retracts. These results show that the feed axes energy demand model in Equation 5 could be used in determining the most energy efficient toolpath strategy. Thus, energy efficiency of toolpaths could be improved by selecting toolpaths with zero tool retracts and longer cutting length with machining being executed along an axis carrying minimum weights.

3. CASE STUDY

3. 1. Experimental Validation for Electrical Energy Demand of Toolpaths with Regards to Feed Axes

Studies were conducted to determine the effects of toolpath strategies on the electrical energy demand of the feed axes. Pocket milling tests were conducted on a 3-axis Takisawa Mac-V3 milling machine. The machine tool is capable of spindle speeds of up to 10,000 *rev/min*. The axes drives were powered by the AC servo motors connected directly to the ball screw drive. The machine and x-axis are directly mounted on the y-axis. The masses for the x- and y-axes, modelled from SolidWorks software are approximately 315 kg and 750 kg, respectively.

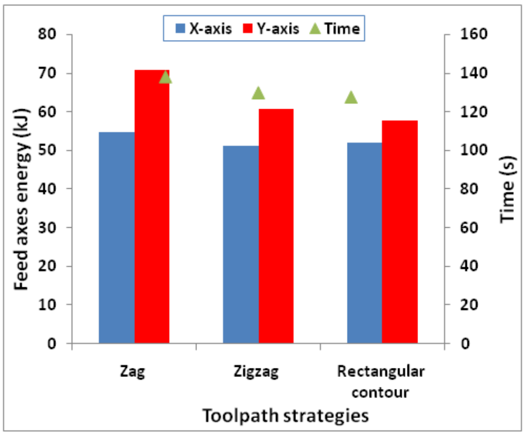


Figure 3. Predicted feed axes energy for different toolpath strategies from analytical method

TABLE 2. Results for cutting time, non-cutting time, and feed axes energy demand of toolpaths

Toolpath strategies	Feed axes energy		Total cycle time to run the toolpath (s)	Cutting time (t) based on G01 (s)
	X-axis (J)	Y-axis (J)		
Zag	54704.29	70716.86	138.13	123.66
Zigzag	51044.30	60790.00	129.82	129.82
Rectangular contour	52040.29	57651.05	127.56	127.56

AISI 1018 steel workpiece material with dimensions of 150 × 100 × 20 *mm* and average mass of 3 *kg* each was cut for the pocket milling tests, and were machined along the x- and y- axes of the Takisawa Mac-V3 milling machine. The density and average hardness of the workpiece are 7.85 g/cm^3 and 233 HV, respectively. The mass of the vice was 57 *kg*. The sample pockets with the considered toolpaths were previously presented in Figure 2. The cutting tests were conducted under dry cutting environment so as to prevent the power of the coolant pump from masking the feed axis power, as well as to promote sustainable manufacture. An 8 *mm* diameter short carbide endmill with 4 flutes was used to perform the pocket milling. The cutting speed was 100 *m/min*. Spindle speed was maintained at 4000 *rev/min*. The depth of cut was kept at 0.5 *mm*. The feedrate was also maintained at 500 *mm/min* to prevent the dominance of feedrates on the feed axes power. The ratio of width of cut to tool diameter was set at 0.75D. The NC codes used in analytically predicting the feed axes energy demand of toolpaths was fed as input to the Takisawa Mac-V3 milling machine for the milling test. The tests were repeated three times for repeatability and accuracy of results. The current and voltage drawn by the CNC machine were directly measured using the 3-phase FLUKE 434 power quality analyser which was clamped by an electrical technician to the three wires supplying current to the machine tool from the power grid as shown in Figure 4. This enabled the calculation of power requirements during the operation of the machine.

The feed axes power was obtained by subtracting the spindle power and the baseline power from the total cutting power [34]. The feed axes power value and the processing time were then used to estimate the electrical energy of the feed axes required for each toolpath strategy. Figure 5 shows the variation of the electrical energy demand for feed axes during milling with different toolpath strategies and axes movements.

From Figure 5, it is observed that the y-axis consumes 15, 14, and 15% more electrical energy of the feed axes than the x-axis of the Takisawa Mac-V3 milling machine for zag, zigzag, and rectangular contour, respectvely. This is because the x-axis is mounted directly on the y-axis. It can be deduced that energy efficiency of toolpaths can be improved by machining along the axis with minimal toolpaths.

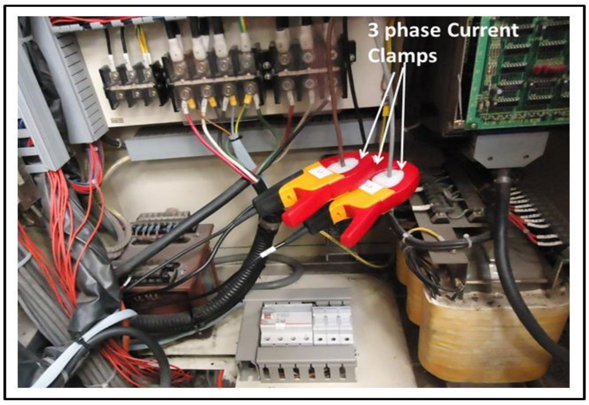


Figure 4. Fluke 434 power quality analyser clamped on three live wires at the back of the Takisawa Mac-V3 milling machine.

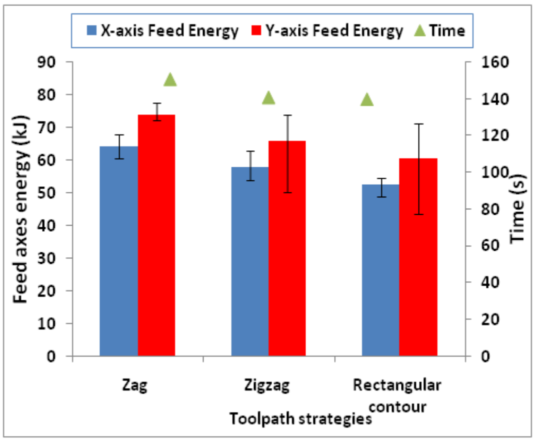


Figure 5. Experimental feed axes energy for different moving weights.

It is also observed from Figure 5 that the rectangular contour toolpath is the most efficient toolpath strategy in terms of electrical energy demand of the feed axes and cycle time due to zero tool retracts and longer cutting length of the pocket. These values are in agreement with the theoretical value deduced and presented in Table 2 where the energy demand of the rectangular contour toolpath strategy is lower along the y-axis.

4. CONCLUSIONS

This paper proposed an approach to analytically determine the most energy efficient toolpath strategy in mechanical machining using the generated NC codes from hyper mill CAM software. This was achieved by evaluating the feed energy requirement of the generated NC codes for each toolpath strategy with a proposed feed axes energy demand model in literature. The analytical method was validated by performing pocket milling on AISI 1018 steel with the zag, zigzag, and rectangular contour toolpaths on a 3-axis Takisawa Mac-V3 milling machine. The following conclusions were obtained from this study:

- Predictions from the analytical method showed that the feed axis energy demand in the y-axis direction was higher than the x-axis by 29, 19, and 11% for the zag, zigzag, and rectangular contour toolpaths, respectively. This is because more weights are moved on the y-axis than on the x-axis.
- Minimum power and electrical energy demand of the feed axes could be achieved by reducing the weights of the table, workpiece, and material billet moved by the feed drive. This is critical since heavier weights increase the friction and inertia exerted on the drive; thereby resulting in a rise in power requirement of the feed axes, and hence the constant power demand of the machine tool.
- The rectangular contour toolpath was the most efficient in terms of energy demand and processing time due to longer cutting length of the toolpath before linking the next cutting pass.
- In case of the zigzag toolpath, the short links between one cutting pass and the next increased the processing time and the feed energy demand by 2%, due to acceleration and deceleration of the machine tool at corners. The feed energy and the processing time for the zagtoolpath were higher by 14 and 8%, respectively than that of the rectangular contour toolpath. This was as a result of the higher number of tool retracts.
- The experimental values show strong correlation with the analytical approach in that the rectangular contour toolpath was identified as the most efficient in terms of feed axes energy and processing time. It is therefore recommended for process planners to select toolpaths with less tool retractions in order to improve the energy efficiency of the machining process.

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Energy Efficiency Analyses of Toolpaths in a Pocket Milling Process

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چکیده

در این مقاله یک آنالیز تحلیلی برای تعیین کارآمدترین ابزار استراتژی در ماشینکاری مکانیکی ارائه شده است. این امر با ارزیابی انرژی الکتریکی مورد نیاز کدهای NC تولید شده برای راه حل های مسیرهای استراتژی زاگ، زایگاگ و خطوط مستطیلی ساخته شده است. روش تحلیلی با انجام مراحل جوش بر روی فولاد AISI 1018 با استفاده از دستگاه تراشکاری ۳ محور Takisawa Mac-V3 مورد تایید قرار گرفت. این خط کش خطی مستطیل بیشتر از نظر تقاضای انرژی برق محور و زمان چرخه کارآمدترین بود. فرزکاری جیبی با استراتژی چرخش زیگزاگ موجب افزایش تقاضای انرژی الکتریکی در محورهای تغذیه و زمان چرخه به میزان ۲ درصد به علت شتاب و ویژگی های کند شدن فرایندهای محور چرخش ماشین ابزار در گوشه های استراتژی ToolPath شده است. همچنین تقاضای انرژی الکتریکی برای محور تغذیه و زمان چرخه برای مسیر ابزار زاگ به ترتیب ۱٤٪ و ۸٪ بیشتر بوده اند، این مورد بخاطر تعداد ابزار استراتژی راه انداز اجرا شده است. دراین مطالعه نتایج اعتبار سنجی تجربی حاصل شده، توافق مطلوبی با آنالیز تحلیلی داشته اند. می توان نتیجه گرفت که برای ماشینکاری پایدار، خط کش خطی مستطیل شکل باید اتخاذ شود، زیرا این روش بدون در نظر گرفتن استراتژی toolpath به کمترین ابزار نیاز داشته، که برای ماشینکاری اتخاذ گردید. برای تولید محصول پایدار، انتخاب پارامترهای سبز بهینه توسط مهندسین فرایند کارخانه حائز اهمیت است.

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