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ORIGINAL ARTICLE

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Software analyses of optimum toolpath strategies from computer numerical control (CNC) codes

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Abstract

This study presents an approach for determining energy efficient toolpaths using numerical control (NC)-based energy demand software. To achieve this, NC programmes were generated for the true spiral, rectangular spiral, and square contour toolpaths from HyperMill, a commercially available Computer-Aided Manufacturing (CAM) software for performing pocket milling of AISI 1018 steel on a 3-axis CNC milling machine. These programmes were uploaded as input on the graphical user interface (GUI) of the NC code-based energy demand software. The result obtained from NC code-based energy software was validated against the theoretical total energy and processing time, and the pocket milling of AISI 1018 steel on a 3-axis CNC milling machine. The theoretical, software, and experimental analyses show that the true spiral toolpath had the lowest total electrical energy demand and processing time. The result also shows that the energy demand software could be adopted to accurately predict the total electrical energy and processing time pre-machining. This could save setting up and trial by error practices and costs. Further studies included surface roughness analyses of the machined pockets after milling, and an improved surface finish of the pocket was obtained with the true spiral toolpath when compared with the other considered toolpaths. Therefore, for energy efficient machining, it is recommended that NC code-based energy demand software which incorporates the weights of feed axes, vice, and workpiece, as well as the power required by the feed drive during cutting should be adopted for the accurate prediction of total electrical energy demand and total processing time of a machining process.

Keywords Energy demand software · NC programmes · Toolpaths · Energy efficiency · Surface roughness

1 Introduction

In 2016, the International Energy Agency (IEA) reported that the total global electricity demand was 20,863 Terawatt hour (TWh), while the industrial sector accounted for 42% (8684 TWh) of the total global electricity demand [1]. The total global CO_2 emissions from fuel combustion were 32.31 Gt CO_2, while the electricity and heat generation accounted for 42% (13.57 Gt CO_2) of the total global CO_2 emissions. Also, the share of emissions from electricity to consuming sectors showed that industry was the largest emitter of CO_2 with 27% [2]. In the UK, in 2016, the Department for Business, Energy and Industrial Strategy reported that the total electricity consumed was 356.7 TWh, while 91.8 TWh which is about 26% of the total electricity consumption was attributable to the industrial sector [3]. Furthermore, the total UK emissions of CO_2 were reported to be 378.9 million tonnes (Mt) of CO_2 equivalent, of which 113.7 million tonnes (Mt) (including power stations and other sources of energy supply) being 30% of the total UK CO_2 emission, and 9.9 million tonnes (Mt) of CO_2 equivalent were attributed to the energy supply and industrial process sectors respectively. Therefore, the use of sustainable technologies and best available practices could provide significant energy savings and CO_2 reduction strategies in the manufacturing sector [4].

Mechanical machining is amongst the widely used technologies in the manufacturing sector due to its versatility and accuracy in the fabrication of products. Milling is predominantly used in the manufacturing industry for producing

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complex geometrical shapes of workpieces [5]. The flexibility and different variables involved in the milling has made it critical to optimise the process in order to obtain higher productivity and quality [6, 7]. One of the methods could be by selecting an optimal toolpath strategy. Toolpaths guide the cutter through the machined region [8], and also position the cutting tool relative to the workpiece through the motion of the machine tool axes [9]. Toolpaths can affect the real machining time as a result of the acceleration and deceleration involved during the different changes in the motion of the machine tool spindle [8, 10, 11]. In addition, minimum manufacturing costs and improved surface finish could be obtained through the selection of an optimum machining toolpath strategy [12] which could include the direction-parallel toolpaths (zag, zigzag), contour-parallel toolpaths (rectangular contour, square contour), and the spiral toolpath strategies. The direction-parallel toolpaths involve the to and fro movement of the cutter in a fixed direction within a boundary on a flat workpiece, while the contour-parallel toolpath consists of a series of contours that are parallel to the boundary or geometry on the flat workpiece [13, 14]. The spiral toolpath involves the initial movement of the cutting tool from the centre of the pocket from which it proceeds spirally outwards. The cutting tool returns to the starting point in each cycle and then cuts outwards to the next outer cycle [15]. This strategy could also involve the motion of the cutting tool from the periphery of the pocket to the inner of the pocket to be machined [16].

1.1 Software-based electrical energy demand and toolpaths evaluation

Electrical energy demand and greenhouse gas (GHG) emissions could be effectively estimated by utilising software-based simulation tools [17]. Software approaches which are utilised to determine optimum conditions for a specific machining operation could minimise the time and cost incurred in procuring materials for experimental analyses. These simulation-based software tools use computer graphics and numerical analysis to improve the productivity and quality of machining operations [9]. Examples include the commercially available CAD/CAM software such as Solidworks and HyperMill. Solidworks software is a plugin that could be used to generate NC codes and to determine the processing time for executing an NC programme. The HyperMill CAM software is integrated into the Solidwork software to generate NC programmes. These software are used in designing and analysing components for mechanical performance as well as its environmental performance. Few researchers have proposed and developed software tools to predict the total electrical energy demand and processing time. For example, Narita et al. [18] developed an environmental burden analyser with numerical data to determine the environmental impacts of machine tool such as electricity consumption and CO_2 emission with regard to the depth of cut, feedrate, spindle speed, and toolpath pattern. CO_2 emission was found to be the dominant environmental burden in machining operations. However, efficient toolpaths with regard to energy demand and processing time were not evaluated with their software and the influence of weights moved by the feed drive was not taken into account. Diaz et al. [19] proposed a web-based energy estimation software for predicting the electrical energy demand and processing time of a given NC programme in order to aid process planners in implementing green machining strategies. The proposed software was validated by performing roughing and finishing of a pocket using NC codes generated from five (5) different toolpath strategies. However, the software does not highlight the weights moved by the feed drive (weight of workpiece, vice, feed axes). Additionally, surface roughness analysis of the machined pockets with different toolpath strategies was not conducted. Vijayaraghavan and Dornfeld [20] proposed a software-based approach for the automation of energy demand prediction at all production levels for life cycle analysis of machine tools. The software utilises 'Complex event processing (CEP)' which handle data reasoning and information processing. The manufacturing technology connect (MT Connect) interface was used to link data from the machine tool and/or other manufacturing equipment to the 'event cloud' for information processing and strategic decision-making. However, the software was not used to determine optimal toolpath strategies.

A web-based and application programming interface (APT) process analysis software with regard to NC codes for predicting the total electrical energy demand and greenhouse gas emission of a machining process when executing a toolpath has been developed [9]. In addition, the authors also investigated the influence of different toolpath strategies on the energy consumption in milling a rectangular pocket. However, the feed axes power in their software was not explicitly modelled to incorporate weights of the machine tool feed axes, workpiece, and machine tool vice. Also, surface roughness analysis of the machined pockets was not performed. The visual basic for application (VBA) software called global reasoning for eco-evaluation of machining (GREEM) has been proposed [21]. This software utilised machining toolpaths (zigzag and contour-parallel toolpath strategies) to estimate the variable energy of the machine tool. However, NC codes were not considered in the software development and surface roughness analysis of the machined pockets was not undertaken in the study.

Few authors also evaluated the energy demand, the processing time, and environmental impact [22] in CNC milling (mould making) and electric discharge machining (EDM) [23]. Although a software tool was utilised in their study [24], the weights moved by the feed drive (i.e. weight of the feed axes, workpiece, vice) were not captured in this study and also the surface roughness of the machined parts with regard to different toolpaths was not investigated. Guo et al. [25] proposed an operation mode-based simulation approach to identify an optimum toolpath strategy. Four toolpath strategies were considered, namely, face turning, straight turning, face and straight turning, straight turning, and face turning. The authors reported that energy efficient machining could be achieved by applying the straight turning machining strategy with the highest parameter settings. Balogun et al. [26] developed an e-smart software based on computer numerical control (CNC) toolpaths and NC codes in order to estimate the total electrical energy demand required to machine a workpiece for linear toolpath. However, other toolpath strategies such as the zag, zigzag, and spiral toolpaths were not considered; weights of materials moved by the feed drive were not incorporated in the e-smart software; and surface roughness of the machined pockets was not investigated in their study. Edem and Mativenga [27] proposed an algorithm for developing energy demand prediction software based on numerical control (NC) codes for estimating the total electrical energy demand and total processing time. The linear and circular toolpaths were considered, and it was reported that shorter linear path lengths (i.e. G01) and circular path segments (i.e. G02 and G03 codes) were highly energy intensive. Nevertheless, the developed NC code-based energy demand software was not used to evaluate optimum toolpath strategies. Additionally, the influence of toolpath strategies on surface roughness of the machined pockets was not investigated in this study.

1.2 Toolpath strategies and surface roughness

It has been reported that toolpath strategies affect the surface roughness of machined parts. For example, Gologlu and Sakarya [15] and Romero et al. [28] studied the effects of zag, zigzag, and spiral toolpath strategies during pocket milling on surface roughness. Improved surface roughness values were reported during pocket milling with the zag and zigzag toolpaths. However, an NC code-based energy demand software was not considered to determine optimum toolpaths in terms of energy demand and processing time. Shajari et al. [29] studied the influence of toolpath strategies (i.e. zigzag, 3D-offset, radial, and spiral) in a finishing process on machining time, surface texture, and cutting forces. They reported that performing finish machining with the radial toolpath resulted in improved surface finish and lower cutting forces. This work did not determine optimal toolpaths using an NC code-based energy demand software. Aramcharoen and Mativenga [30] and Souza et al [31] assessed the electrical energy demand of various machining toolpaths. They showed that the contour and spiral toolpath strategies reduced energy demand by up to five (5) times when compared with the zigzag toolpath. Nevertheless, energy demand software which incorporates the weights of materials moved by the feed axes was not considered. Edem and Mativenga [10] studied the effects of toolpath strategies on the electrical energy demand of feed axes when performing pocket milling of AISI 1018 steel along the *x*- and *y*-axes directions of a 3-axis CNC milling machine. Results from this study showed that the feed axes energy demand and processing time, as well as the surface roughness values were minimal when performing pocket milling with the rectangular contour toolpath. However, NC code-based energy demand software was not used to determine optimal toolpaths. Altintas et al. [32] studied the influence of machining toolpaths on the total electrical energy requirements and total operation time when milling a rectangular open pocket STEP feature. Siemens NX 9.0 was used to generate the considered toolpaths which include follow path, follow periphery, profile, zig, zigzag, and the zig with contour toolpath strategies. It was found that the zigzag toolpath strategy resulted in minimum energy consumption when compared with other toolpaths. Nevertheless, no energy demand prediction software was developed to estimate the total electrical energy and processing time of different toolpath strategies. Also, surface roughness studies of the machined pockets were not undertaken. Edem et al. [8] studied the effect of toolpaths on the electrical energy demand of two CNC milling machines during pocket milling of AISI 1018 steel. Results show that electrical energy demand was higher along the feed axis of both machine tools carrying more weights. However, this study did not determine optimum toolpaths in terms of energy demand with NC code-based energy demand software, and surface roughness analyses of the machined pockets was not undertaken. Recently, Edem and Balogun [33] proposed an analytical approach for evaluating the energy demand of feed axes based on NC codes for the zag, zigzag, and rectangular contour toolpath strategies. The analytical model was validated by conducting pocket milling with the aforementioned toolpath strategies on a rectangular block of AISI 1018 steel using a 3-axis CNC milling machine. They reported that minimum electrical energy demand of the feed axes and lower processing time were achieved when performing pocket milling with the rectangular contour toolpath while the zigzag toolpath resulted in higher energy demand of the feed axes and processing time by 2%. This work however has some limitations in that NC code-based energy demand software was not used to determine energy efficient of spiral toolpaths, and surface roughness of the machined pockets was not considered.

From literature, it can be observed that energy demand software based on NC codes has not been explored and the advantages of its applications to determining the optimum machining strategies have not been considered. This work therefore is aimed at exploring this new area in order to determine energy efficient machining toolpaths. This is of great importance to machinists and production planning experts for sustainable manufacture that applies the best available practices in the machining science. Thus, process planners and machine tool operators could be better informed in taking decisions during the generation and selection of toolpath strategies using any of the commercially available CAM software.

1.3 Research aim

The aim of this research is to develop an approach to determine efficient toolpaths with regard to total electrical energy demand and total processing time from NC programmes. To achieve this, the true spiral, rectangular spiral, and square contour toolpath strategies were generated and evaluated using the NC code-based energy demand software. The predicted results from the software were compared with those obtained from theoretical analyses and from direct measurement of the total electrical energy and total processing time when performing pocket milling of AISI 1018 steel workpiece on a 3-axis Takisawa Mac V3 milling machine.

2 Modelling the total electrical energy demand of toolpaths from NC codes: theoretical and software approaches

Edem and Mativenga [27] proposed a model to evaluate the total electrical energy required to perform pocket milling operations with different toolpath strategies on flat workpiece materials as presented in Eqs. (1a), (1b) and (1c).

$$E_{total} = E_{baseline} + E_{tool\_change} + E_{spindle\_run} + E_{cut} + E_{feed} + E_{coolant} \quad (1a)$$

where E_{total} is the total electrical energy demand in mechanical machining in J, $E_{baseline}$ is the energy required by auxiliary and peripheral units in J, E_{tool_change} is the energy consumed at tool change in J, $E_{spindle\_run}$ is the energy required for the spindle in J, E_{cut} is the energy required for material removal in J, E_{feed} is the energy consumed by the feed drives in J, and $E_{coolant}$ is the energy required by the coolant pump motor in J.

The energy for baseline, tool change, feed axes, spindle run, and cutting in Eq. (1a) was expanded to include their corresponding power and time as presented in Eq. (1b).

$$E_{total} = P_{baseline} \cdot t_{baseline} + P_{tool\_change} \cdot t_{tool\_change} + P_{spindle\_run} \cdot t_{spindle\_run} + P_{cut} \cdot t_{cut} + P_{feed} \cdot t_{feed} + P_{coolant} \cdot t_{coolant} \quad (1b)$$

where $P_{baseline}$ is the power required by auxiliary and peripheral units in W, P_{tool_change} is the power consumed during tool change in W, $P_{spindle\_run}$ is the power required to run the spindle in W, P_{cut} is the power required for material removal in W, P_{feed} is the power consumed by the feed drives in W, and $P_{coolant}$ is the power required by the coolant pump motor in W. $t_{baseline}$, t_{tool_change}, $t_{spindle\_run}$, t_{cut}, t_{feed}, and $t_{coolant}$ represent the baseline, tool change, spindle run, cutting, feed, and coolant time, respectively.

It should be noted that the feed power, which is the sum of the rapid feed power (tool approach and tool retract) and feed axes power could be estimated using the model proposed in Edem and Mativenga [33, 34] which takes into account the weight of the axes, workpiece, and machine tool vice.

Thus,

$$P_{feed} = P_{G01/G02/G03-feed} + P_{G00-feed(approach)} + P_{G00-feed(retract)}$$

where $P_{G01/G02/G03\ (feed)}$ is the feed power demand for the linear and circular toolpaths in W, while $P_{G00-feed(approach/retract)}$ is the power demand for rapid move during tool approach or tool retract in W.

The actual feedrates moved by each axes are then incorporated into the proposed power demand models to estimate the power demand of feed axes or during rapid move. Detailed estimation of linear interpolation from the length of travel (L) and the actual feedrates moved by each axis from the command feedrate or rapid feedrate is provided in Edem and Mativenga [34].

Further modifications of Eq. (1b) resulted in the inclusion of models for the spindle run power and tool change power [35], as well as cutting power, rapid feed power, and the feed axes power as in Eq. (1c).

$$E_{total} = P_{baseline} \cdot t_{baseline} + P_{tool\_change} \cdot t_{tool\_change} \times \left[\mathrm{INT}\left(\frac{t_{cut}}{T_L}\right) + 1 \right] + (mN + C) \cdot t_{spindle\_run} + (kQ) \cdot t_{cut} + (P_0 + (a_i W_i v_{f_i} + b_i W_i + F_f v_{f_i})) \cdot t_{G01/G02/G03-feed} + (6502 v_{f_a} + 2838.3 + F_f v_{f_a}) \cdot t_{G00-feed(approach)} + (8540 v_{f_a} + 2852 + F_f v_{f_i}) \cdot t_{G00-feed(retract)} + P_{coolant} \cdot t_{coolant} \quad (1c)$$

where E_{total} is total electrical energy demand in mechanical machining in J; $P_{baseline}$, P_{tool_change}, and $P_{coolant}$ still retain their usual meanings, P_0 is the baseline power (in the feed axis equation) in W, while T_L is the tool life in minutes; $t_{baseline}$, t_{tool}

$_{\_change}$, $t_{spindle\_run}$, t_{cut}, t_{feed}, and $t_{coolant}$ still retain their usual meanings while $t_{G01/G02/G03}$, $t_{G00-feed(approach)}$, and $t_{G00-feed(retract)}$ are the time required at rapid feed during tool approach, time required at rapid feed during tool retract in *s*, respectively. Also, v_{f_i} is the rapid feed or table feedrate in the specified axis (i.e. *x*-axis or *y*-axis) direction, while v_{f_a} is the specified or rapid feedrate for tool approach or tool retract in *z*-axis direction, $mN+C$ is the spindle speed characteristic model in *W*, *k* is the specific cutting energy of the material in J/mm^3, *Q* is the material removal rate in mm^3/s, a_i and b_i are constants in the specified axis direction, W_i is the weight of the axis, workpiece, and machine vice in the specified axis direction, and F_f is the feed force.

The feed power required when cutting in Eq. (1c) can be calculated from the feed force (F_f) and the table linear feed velocity (v_f) as shown in Eq. (1d).

$$F_f = XKa_p f_z^x \sin\varphi^x \tag{1d}$$

where *X* is the ratio of the feed force to the cutting force in milling, *K* is the specific cutting resistance in N/mm^2, a_p is the depth of cut, a_p is the feed per tooth, φ is the swept angle in machining, and *x* is a constant based on cutting variables.

Thus, cutting conditions in Eq. (1d) are incorporated into energy analysis for an individual machine table axis which presents a good link to optimisation of energy consumption at the process planning stage [34].

2.1 Theoretical estimation of total electrical energy demand and processing time for different toolpaths from NC codes

The CAD model shown in Fig. 1 contains the geometric and dimensional specifications of the part designed in CAD software (Solid works) with the specified toolpath strategies (i.e. true spiral, rectangular spiral, and the square contour toolpath strategies with a length and width of 70 mm respectively).

This CAD model was then exported as an input and opened in CAM software (HyperMill) where NC codes for the aforementioned toolpaths were generated according to parameters such as type of CNC machine; cutting tools; workpiece materials, coolant; and feed axes direction. The proposed framework adopted for generating NC codes for the specified toolpaths is presented in Fig. 2.

The generated NC programmes for the specified toolpaths in Fig. 1 were used to theoretically estimate the total electrical energy required to perform pocket milling on a square workpiece based on Eq. (1c). This was achieved by summing the energy demand of each block of NC code (i.e. obtained from the power demand and processing time) for the true spiral, rectangular spiral, and square contour toolpaths respectively. Detailed explanation on the estimation of the electrical energy demand of each energy consuming component based on their corresponding NC codes and the time required to run an NC block is provided in Edem and Mativenga [27] and Edem [36].

Figure 3 shows results for the theoretical estimation of total energy demand and total processing time for the true spiral, rectangular spiral, and square contour toolpaths based on their respective NC codes.

From Fig. 3, it could be deduced that lower energy demand and processing time could be achieved when performing pocket milling with the true spiral toolpath strategy. This means that total electrical energies required for performing pocket milling with the rectangular spiral and square contour toolpaths are higher than that of the true spiral toolpath by 15% and 22% respectively, while their corresponding total theoretical times are 20% and 26% higher than that of the true spiral toolpath.

2.2 Optimum toolpaths prediction with NC code logic

The model in Eq. 1(c) was used to implement the NC code-based energy demand software. Figure 4 presents the logic for determining the total energy and processing time from NC code based on the proposed energy demand software.

From Fig. 4, the generated NC programmes for each of the specified toolpath strategies, from which parameters such as feedrate (v_f) and depth of cut (a_p) were acquired are first uploaded as input on the Graphic

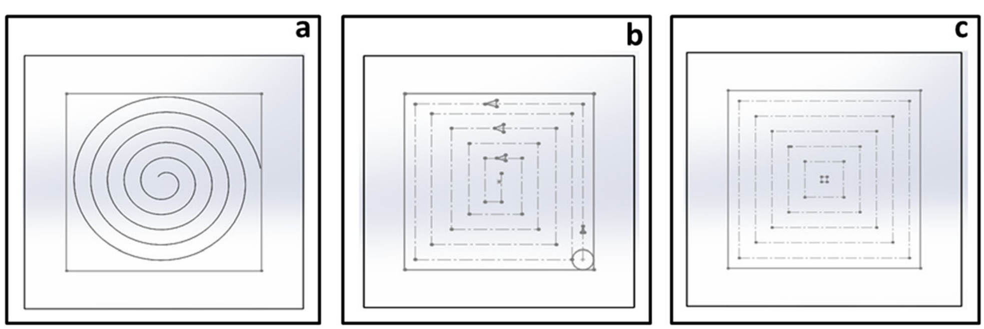


Fig. 1 Toolpath strategies: **a** true spiral, **b** rectangular spiral, and **c** square contour

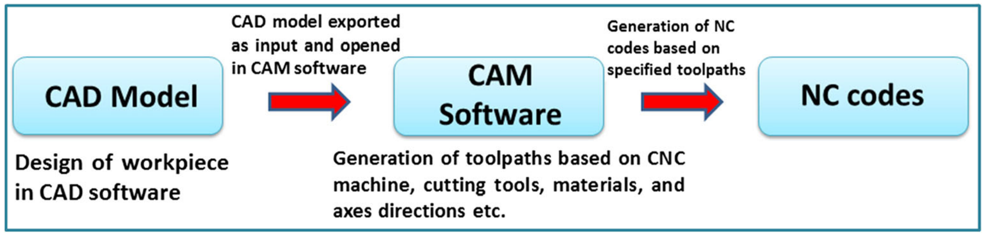


Fig. 2 Toolpath and NC codes generation

User Interface (GUI). Additional inputs such as the machine tool parameters (i.e. type of machine tool, baseline power, weights of the *x*-axis and *y*-axis, and the weight of the machine tool vice); cutting parameter (width of cut (a_e)); workpiece parameters (i.e. workpiece material, workpiece weight, specific cutting pressure of the material (K) for calculating the feed force, and the specific cutting energy (k) of the material for calculating the cutting power); and the cutting tool parameters (i.e. tool diameter, number of flutes) are also required as input for the estimation of the total electrical energy and processing time of each of the specified NC programme. The total electrical energy and processing time of each of the NC programme for the specified toolpath strategies are predicted by clicking the 'RUN' button. The results are as shown in Fig. 5.

From Fig. 5, it is observed that the true spiral toolpath is the most efficient toolpath strategy with regard to lower electrical energy requirement when compared with the rectangular spiral and square contour toolpaths which have 13% and 15% higher energy demand respectively than the true spiral toolpath. The true spiral toolpath also resulted in lower processing time, while the rectangular spiral and square contour toolpaths had higher processing times of 18% and 24% respectively.

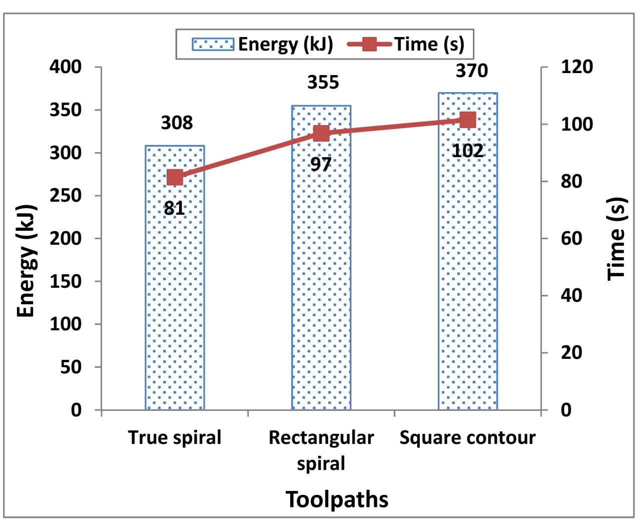


Fig. 3 Theoretical estimation of total electrical energy demand and processing time for different toolpaths

3 Case study

In order to compare the theoretical results, experimental analysis with the predicted result from NC code-based energy demand software, pocket milling of AISI 1018 steel with the true spiral, rectangular spiral, and the square contour toolpaths was undertaken in a dry cutting environment. The pocket milling process was conducted on the 3-axis Takisawa Mac-V3 milling machine with a DC servo motor model 20M, spindle model A06B-0652-B, and FANUC controller. The spindle speed of this vertical milling machine centre could reach up to 10,000 rev/min, while the spindle motor has a rated power of 7.5 kW.

The *x*-, *y*-, and *z*-axes accelerate at 10 m/s^2. In addition, the *x*- and *y*-axes have a rated power of 0.85 kW, while that of the *z*-axis is 1.2 kW. The feed axes' drives are powered by the AC servo motors which are connected directly to the ball screw drive. The machine tool's table and *x*-axis are directly mounted on the *y*-axis. The table mass was modelled in Solid Works 2012 software, and the values for the *x*- and *y*-axes were obtained from the mass properties section of the aforementioned software to be approximately 315 kg and 750 kg respectively [8, 10].

The as-received cast and hot rolled AISI 1018 steel flat bar of 080A15 specification was cut into 100 × 100 × 20 mm for the pocket milling process. Details of the workpiece and cutting parameters are presented in Tables 1 and 2.

The depth of cut was kept constant at 0.5 mm in order to reduce vibrations that could result from the cutting forces during machining thereby increasing energy loss due to vibration and noise. Pocket milling of the three equal sized AISI 1018 steel square blocks were machined with the true spiral, rectangular spiral, and square contour toolpath strategies. The pocket has a dimension of 70 mm × 70 mm. The toolpaths were generated using the HyperMill CAM software. The ratio of width of cut to tool diameter was set at 0.75 in order to reduce friction at the cutting edge and to increase tool life. Dry cutting environment was utilised so as to promote sustainable machining. The weight of vice on the Takisawa Mac-V3 milling machine was 570 N while the coolant pump consumed 400 W. The electrical current drawn during the machining process was measured and recorded with the three-phase Fluke 434 power quality analyser. The cutting tests were

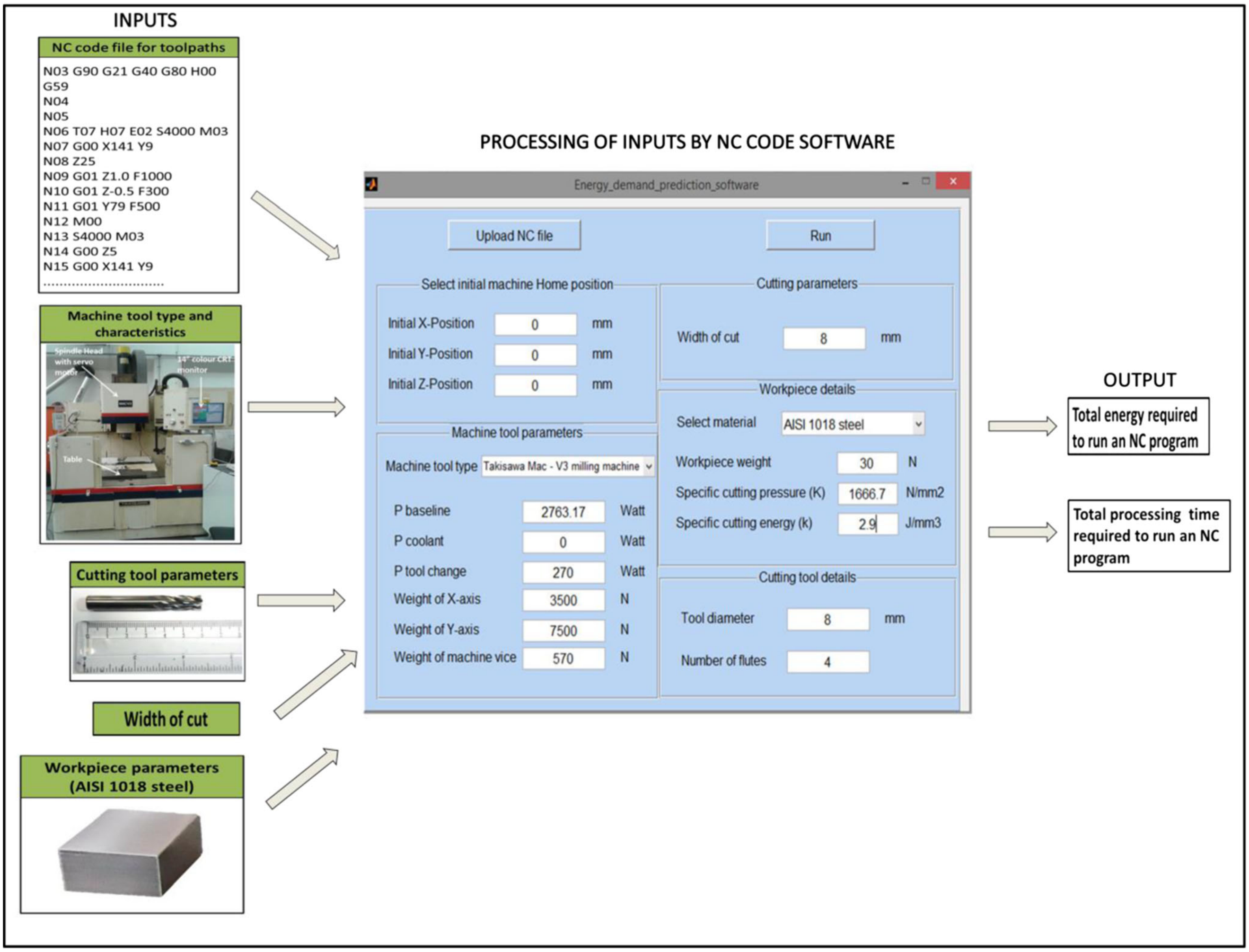


Fig. 4 Logic for determining total energy and total processing time with NC code-based energy demand software

repeated three times for consistencies. A new cutter was used for the pocket milling of each new toolpath in order to reduce the influence of tool wear. Furthermore, the surface roughness of each of the machined toolpaths was determined using the Surtronic 25 portable surface roughness checker.

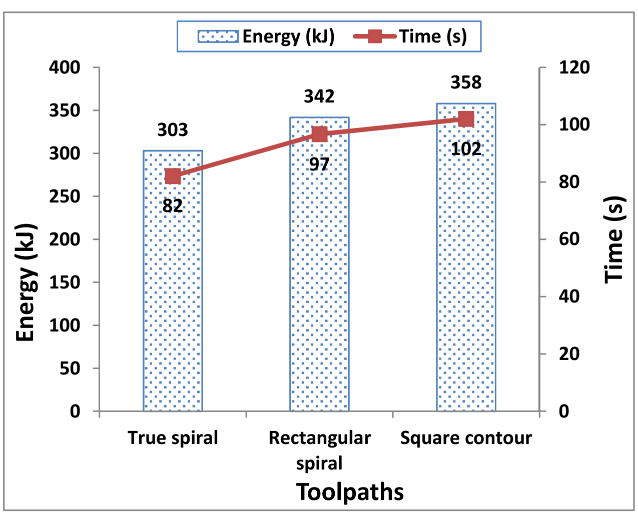


Fig. 5 Predicted total energy and time for different toolpaths from NC code-based energy software

3.1 Energy evaluation from machining

Figure 6 presents the measured electrical energy demand and total processing time for different toolpath strategies during pocket milling of AISI 1018 steel workpiece.

From Fig. 6, the measured total electrical energy requirements for pocket milling of AISI 1018 steel square workpieces with the true spiral, rectangular spiral, and square contour toolpaths were 311, 358, and 374 kJ respectively. It is also observed that the true spiral toolpath strategy is the most efficient in terms of energy requirements for the pocket milling process, with energy savings of 15% and 20% when compared with the rectangular spiral and square contour toolpaths respectively. Furthermore, the measured total processing time for pocket milling of AISI 1018 steel square workpieces with the true spiral, rectangular spiral, and square contour toolpaths were 84, 100, and 105 s respectively. Thus, pocket milling

Table 1 Workpiece parameters

Workpiece material	AISI 1018 steel
Chemical composition of workpiece	0.17% C, 0.27% Si, 0.80% Mn, 0.050% S max, 0.050% P max
Workpiece hardness, Vickers (HV)	191, 236, 226, 224, 236, 287 Average = 233.3
Mass of workpiece (kg)	2

with the true spiral toolpath resulted in minimum total processing time when compared with the rectangular spiral toolpath and square contour toolpaths with higher processing time of 19% and 25% respectively.

The reason for the minimum energy demand and processing time achieved when performing pocket milling with the spiral toolpath strategy may be due to the fact that few changes are made in the cutting direction which results in less accelerations and decelerations of the machine tool at sharp corners. However, the presence of sharp corners in the rectangular spiral and square contour toolpaths leads to higher energy demand as a result of the accelerations and deceleration of the tool at these corners. The results in Figs. 3, 5, and 6 show that lower processing time leads to minimum energy demand, which therefore indicates a good correlation between cycle time and energy demand.

3.2 Comparison of results between theoretical estimation, software prediction, and experimental analysis

The graph in Fig. 7 shows a comparison of results for the total electrical energy demand and total processing time between the theoretical estimation, measured data, and NC code-based energy demand prediction software.

From Fig. 7, the theoretically estimated energy demand results correlates with the predicted results from NC code-based software for the true spiral, rectangular spiral, and square contour toolpaths by 1.7%, 3.8%, and 3.4% respectively. Also, the measured total electrical energy demand for the three specified toolpaths correlates with the predicted results from the NC code-based software by 2.6%, 4.7%, and 4.5% respectively.

Furthermore, the theoretically estimated total processing time correlates with the predicted total processing time from NC code-based software for the true spiral, rectangular spiral, and square contour toolpaths by 1.2%, 0.4%, and 0.5% respectively. In addition, the measured total processing time for the three specified toolpaths correlates with the predicted time from the NC code-based software by 2.4%, 3.1%, and 2.9% respectively. The slight increase in values of the total theoretical electrical energy and total processing time may be as a result of errors, while the slight increase in values of the total measured electrical energy demand and the total processing time may be as a result of the surge in power demand which usually occurs at spindle start up and at the initialisation of feed axes movement, as well as machine tool decelerations at sharp corners and accelerations at the beginning of the next toolpath segment which were not considered in the software.

The results obtained in this study show that accurate prediction of total energy demand of a machining process, as well as making informed decisions on the selection of efficient toolpath strategies could be achieved by utilising NC code-based energy demand prediction software. Therefore, to achieve sustainable and energy efficient machining, it is recommended that the NC code-based energy demand software be adopted.

Table 2 Cutting parameters

Machine tool	Takisawa Mac-V3 milling machine
Cutting tool type	SWT-161-5008A 8 mm short carbide end mill
Number of teeth/flutes, z	4
Feedrate v_f, (mm/min)	500
Spindle speed, N (rev/min)	4000
Cutting tool diameter D, (mm)	8
Depth of cut a_p , (mm)	0.5
Width of cut, (mm)	0.75D
Cutting speed V_c, (m/min)	100

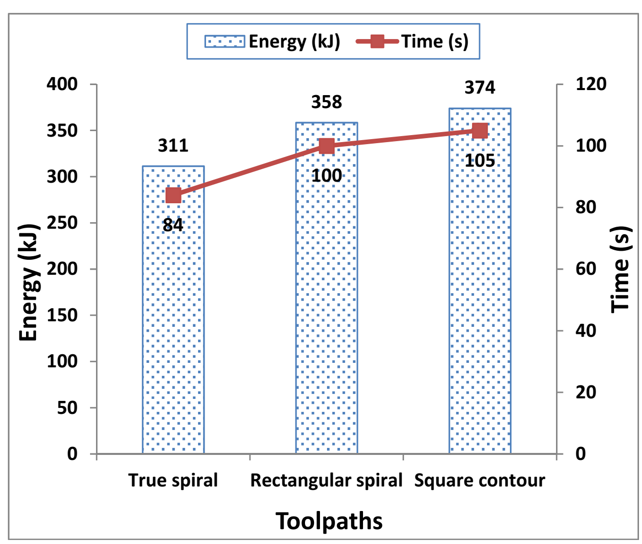
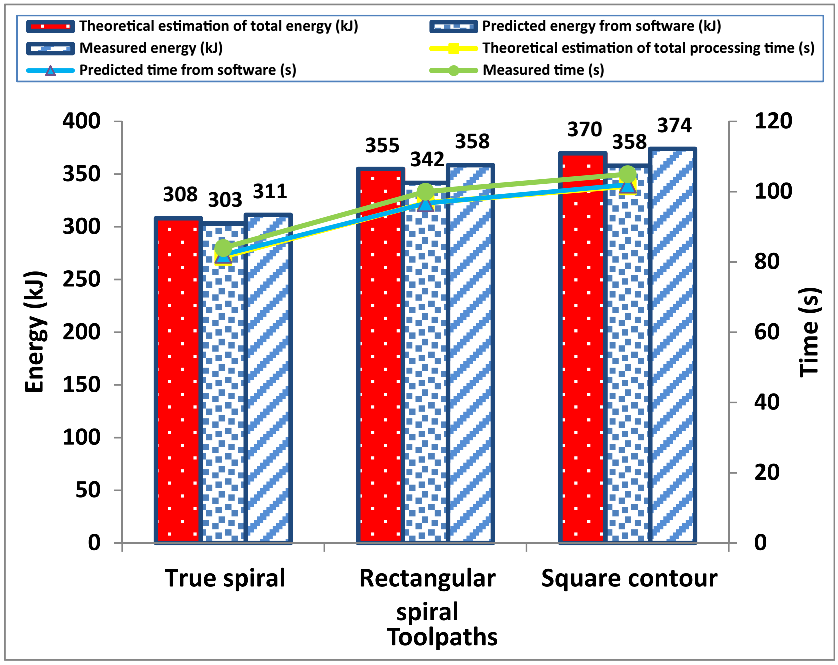


Fig. 6 Measured energy and time for different toolpaths

Fig. 7 Comparison between measured data and NC code-based software for determining optimum toolpaths



4 Influence of toolpaths on surface roughness

Further studies were undertaken to determine the influence of true spiral, rectangular spiral, and square contour toolpath on surface roughness of the machined square pockets. In order to achieve this, surface roughness of the machined part was measured with Surtronic 25 surface roughness checker. The Surtronic 25 portable surface roughness checker is a portable stylus type instrument with the stylus travelling over the machined surface [36]. Three different points on the machined surface were measured to determine the average surface roughness. Readings at each point were undertaken three times. Figure 8 presents graph showing variations of average surface roughness with the specified toolpath strategies.

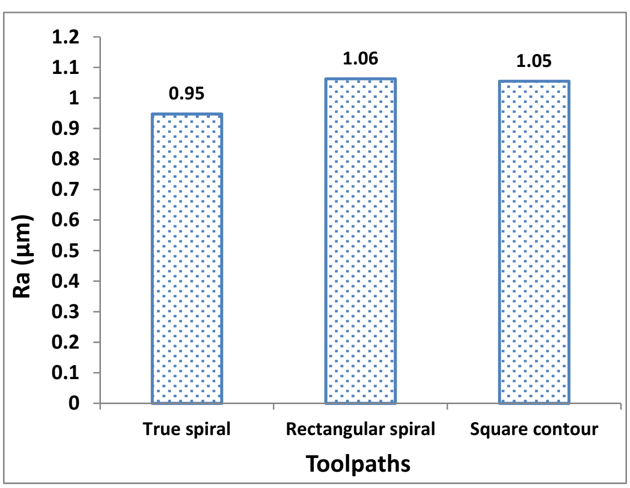


Fig. 8 Surface roughness for machining toolpaths

From Fig. 8, it is observed that surface roughness values for the square pockets machined with the true spiral, rectangular spiral, and square contour toolpaths are 0.95, 1.06, 1.05 μm. Results show that the true spiral toolpath has the lowest surface roughness value when compared with the rectangular spiral and square contour toolpaths. This is true because the true spiral toolpaths has constant cutting loads that are maintained during the cutting process.

5 Conclusions

This study proposes theoretical estimation, software based, and experimental approaches for determining efficient toolpaths with regard to the total electrical energy demand and processing time from NC programmes generated for the true spiral, rectangular spiral, and square contour toolpath strategies. The following conclusions were obtained from the study:

- The total estimated theoretical electrical energy demand for the true spiral, rectangular spiral, and square contour toolpath strategies were 308, 355, and 377 kJ respectively, while the total theoretical processing time for the aforementioned toolpaths were 81, 97, and 102 s respectively. Thus, the total electrical energies for the rectangular spiral and square contour toolpaths were higher than that of the true spiral toolpath by 15% and 22% respectively, while their corresponding total theoretical times were also 20% and 26% higher respectively.

- The total electrical energy requirements for running NC programmes generated for pocket milling with true spiral, rectangular spiral, and square contour toolpaths were predicted to be 303, 342, and 358 kJ respectively using the NC code-based energy demand prediction software, while the total processing times were 82, 97, and 102 s respectively. It was observed that the energy demands for the rectangular spiral and square contour toolpaths were 13% and 15% higher respectively, while the total processing times were also high by 18% and 24% respectively than that of the true spiral toolpath.
- The measured total electrical energy requirements for pocket milling of AISI 1018 steel square workpieces with the true spiral, rectangular spiral, and square contour toolpaths were 311, 358, and 374 kJ respectively. It was also observed that the true spiral toolpath resulted in energy savings of 15% and 20% when compared with the rectangular spiral and square contour toolpaths respectively. Furthermore, the measured total processing time for the specified toolpaths was 84, 100, and 105 s respectively. Thus, pocket milling with the true spiral toolpath resulted in minimum total processing time when compared with the rectangular spiral and square contour toolpaths with higher processing time of 19% and 25% respectively.
- The theoretically estimated energy demand results correlates with the results from NC code based energy software for the true spiral, rectangular spiral, and square contour toolpaths by 1.7%, 3.8%, and 3.4% respectively. Also, the measured total electrical energy demand correlates with the results from the NC code-based software by 2.6%, 4.7%, and 4.5% respectively.
- The theoretically estimated total processing time correlates with the predicted total processing time from NC code-based software for the true spiral, rectangular spiral, and square contour toolpaths by 1.2%, 0.4%, and 0.5% respectively. In addition, the measured total processing time for the three specified toolpaths correlates with the predicted time from the NC code-based software by 2.4, 3.1, and 2.9% respectively.
- Accurate prediction of total electrical energy demand of a machining process, as well as making informed decisions on the selection of efficient toolpath strategies could be achieved by utilising NC code-based energy demand software.
- In order to achieve sustainable and energy efficient machining, this study therefore recommends the use of NC code-based energy demand software which incorporates the weights of feed axes, vice, and workpiece, as well as the power required by the feed drive during cutting (feed power) for the accurate prediction of total energy demand and total processing time of a machining process.
- The surface roughness values for the square pockets machined with the true spiral, rectangular spiral, and square contour toolpaths were 0.95, 1.06, and 1.05 μm respectively. This means that the true spiral toolpath has the lowest surface roughness value when compared with the rectangular spiral and square contour toolpaths as a result of constant cutting loads maintained during the cutting process due to the absence of sharp corners when performing pocket milling with the true spiral toolpaths.
- It can generally be inferred that for sustainable and green manufacturing practices, spiral toolpath should be encouraged. This sustainable machining strategy promotes lower processing time that leads to minimum energy demand and better surface finish. This is an indication of a green and sustainable machining process. Sustainable manufacturing processes can be promoted by adopting this strategy.

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