Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 35 (2019) 567–572

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

2nd International Conference on Sustainable Materials Processing and Manufacturing

(SMPM 2019)

Sustainable selection of optimum toolpath orientation in milling AISI 1018 steel alloy

Vincent A. Balogun[a]*, Isuamfon F. Edem[b]

[a]Faculty of Engineering, Department of Mechanical Engineering, Edo University Iyamho, Edo State, Nigeria
[b]Faculty of Engineering, Department of Mechanical Engineering, Akwa Ibom State University, MkpatEnin, Akwa Ibom State, Nigeria.

Abstract

Toolpath orientations and axes weights have been identified as some of the parameters that could influence the electrical energy consumption and sustainable machining objectives. However, power evaluations of the machine tool axes when carrying different weights and in different toolpath trajectories have not been fully implemented for energy management in machining processes. This work proposes a framework for determining optimum toolpath orientations by conducting a comparative study and individualization analysis of axes weights for electrical power consumption management in slot milling operations of AISI 1018 steel alloy. Results show that performing slot milling at an angle aligned in the direction of the axis with the minimum weights tend to lower the feed axes power consumption.. Therefore, sustainable slot milling operations could be achieved by aligning the toolpaths at an angle oriented in the direction of the lighter axis for minimum feed axes power consumption. This work could further enhance the modeling of power consumption, and hence electrical energy demand in mechanical machining for resource efficiency and green manufacturing.

Peer-review under responsibility of the organizing committee of SMPM 2019.

Keywords: AISI 1018, machining, sustanability, toolpath

* Corresponding author. Tel.: +2348036434484.
E-mail address: vincent.balogun@edouniversity.edu.ng

2351-9789
Peer-review under responsibility of the organizing committee of SMPM 2019.
10.1016/j.promfg.2019.05.080

1. Introduction

Sustainable manufacturing strategy has forced most manufacturers to devise different methods of product fabrication with reduced production costs and electrical energy demand. This is because of high energy bills, soaring production costs and increased environmental impacts [1], hence the encouragement of efficient manufacturing through the optimization of manufacturing processes. Mechanical machining is the commonly used technologies for manufacture due to its flexibility and precision during the fabrication of consumer products [2, 3].

Machine tools require electrical energy to perform machining tasks. It has been reported that about 90% of the environmental impacts are as a result of the electricity consumption of machine tools [4] and hence, its continued increase in environmental pollution throughout its use phase [5]. This has led to the introduction of strict laws and regulations that could mitigate its energy consumption and carbon footprints globally [6-10].

1.1. Toolpath orientations

Toolpath is the cutting tool movement and direction defined by the user and could be defined by the computer aided manufacturing (CAM) software. The cutter is guided through the machined region by the toolpaths that facilitates the material removal to a fixed depth from some arbitrary closed boundary on a flat workpiece surface. They can be adopted for pocketing [11-13] and/or slotting (simple cavity which could be open or closed, straight, angular and circular etc. [14]. Efficient toolpath orientations could result in minimum cycle time, surface finish improvement, increased tool life [15], and minimum energy demand [16].

Few researchers utilized analytical methods to determine optimal toolpath orientations in milling. For example, Baptista et al. [17] showed that machining time was minimal in the 0° direction and higher in the 90° direction. Park et al. [18] developed a toolpath planning algorithm to determine the optimal inclination angle between 0° and 90° with minimum number of tool retractions, and the number of elements for the zag and zigzag toolpaths. Monreal and Rodriguez [19] proposed a mechanistic approach to evaluate the cycle time when performing pocket milling with the zigzag toolpath at different angle of orientations including 0°, 30°, 60°, and 90°. Rangarajan and Dornfeld [20] reported that minimum cycle time was achieved when machining at 36.9° representing about 2 – 4% of energy savings. This work however ignored the optimum toolpath orientation for sustainable manufacture. He et al. [21] conducted a research to determine an analytical method of power demand for two axes feed motors. This work was based on numerical control (NC) codes. However, authors did not consider the effects of workpiece, machine vice and axes weights for the analytical solutions of the power and the optimum toolpath orientations for energy consumption reduction. Kong et al. [22] reported that for the maximum feedrate of the machine axes in the x-y plane to be exhibited, the angle of orientation of the machine tool axes should be 45°. However, the authors ignored the impact of toolpaths' angles of orientation. Edem and Mativenga [23] reported an strategy to determining toolpaths with lower energy intensity. They reported that in the choice of toolpaths that could enhance the optimization of energy intensity in mechanical machining, linear path segments with longer paths should be adopted. .

The reviewed literature has highlighted the different methods used by few researchers to determine sustainable and efficient toolpath orientations with regards to the machining time. However, it could be inferred that the proposed studies did not develop a framework for determining the optimum toolpath orientation, as well as conduct a comparative study and analysis of the machine tool axes weights for minimum power demand in milling AISI 1018 steel. This gap is addressed in this study.

1.2. Research aim

This work is aimed towards the development of a new framework that could be adopted to determine the optimal toolpath orientation, and to conduct a comparative study and individualization analysis of machine tool axes weights for electrical power consumption management. This was achieved through the milling of slots on the AISI 1018 steel alloy at various toolpath orientations. The milling was conducted on the Takisawa Mac-V3 milling machine while the electric current demand was recorded. This was necessary to identify the most sustainable toolpath orientation in terms of minimum feed axes power demand.

2. Research and experimental strategy

The 3-axis Takisawa Mac-V3 milling machine was adopted for the milling tests. The electrical power demand during slot milling of AISI 1018 steel were assessed at different toolpath angles of 0º, 15º, 30º, 45º, 60º, 75º and 90º. The Takisawa Mac-V3 milling machine is a CNC vertical machining centre with FANUC control system. This milling machine's spindle designated A060-0652-B can hold up to 80 *mm* cutter diameters with a variable spindle speeds maximum of 10,000 *rev/min* controlled by a Direct Current 20M servo motor model with a rated power of 7.5 *kW*, and the machine tool's feedrates are 12000 *mm/min* for the x and y axis, and up to 10,000 *mm/min* for the z axis. The worktable dimension and work envelope is 600 × 400 *mm* with a permissible load of 200 *kg*. The x axis of the CNC milling machine tool is mounted directly on the y axis, thereby making the y axis to carry more weights than the x axis. The modeled x and y axes masses on Solid works software are roughly 315 *kg* and 750 *kg* respectively [24, 25].

A billet blank stock of AISI 1018 steel alloy which is a general purpose carbon steel that is easily machined and welded, was cut into 150 × 100 × 20 *mm* with a mass of 3 *kg* as shown in Figure 1.

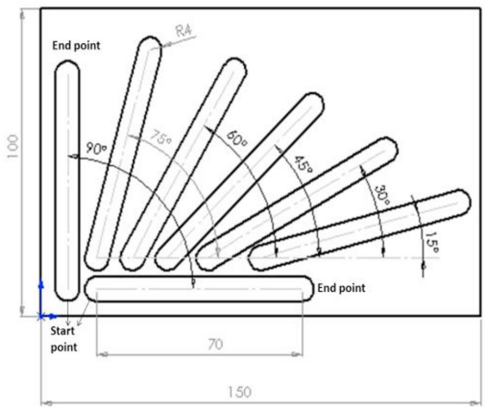

Fig. 1. Linear toolpaths at different angles of orientation

The NC codes for the slot milling operation at different toolpath orientations were created with the Hypermill computer aided manufacturing (CAM) software based on the workpiece presented in Figure 1.

The coordinates for each axis and NC codes obtained from the Hyper mill computer aided manufacturing (CAM) software are as shown in Table 1.

Table 1. Machining efficiency and effects

Angle of orientation (degrees)	**Position**	**Numerical control (NC) code (Linear toolpaths with tool movement)**	
		X-axis	**Y-axis**
90	Starting point	X 9.00	Y9.00
	Ending point	X 9.00	Y79.00
75	Starting point	X 19.00	Y19.00
	Ending point	X 37.12	Y86.61
60	Starting Point	X 31.00	Y19.00
	Ending point	X 66.00	Y79.62
45	Starting Point	X 43.00	Y19.00
	Ending point	X 92.50	Y68.50
30	Starting Point	X57.00	Y19.00
	Ending point	X117.62	Y54.00
15	Starting Point	X 75.00	Y19.00
	Ending point	X142.61	Y37.12
0	Starting Point	X19.00	Y9.00
	Ending point	X89.00	Y9.00

The workpiece was clamped firmly on the machine vice along the x-y plane of the machine table. The vice weighed 57 *kg*. The spindle speed and the depth of cut remained constant at 4000 *rev/min* and 0.5 *mm* respectively while the feedrate was kept at 500 *mm/min*. The cutting tests were conducted by first identifying the current and voltage measurement point at the machine tool electrical panel. The electrical current and voltage requirements of the machine tool were measured through direct contact with the aid of the 3-phase FLUKE 434 power quality analyzer based on ISO 14955-1:2014 [26] definition of machine tools operating states, through which the calculation of power requirements of the machine tool was evaluated during machining operations.

Air cutting and slot milling were undertaken as the tool executes linear toolpaths at varying angles from 0º to 90º (i.e. in the x axis, y axis, and x and y axes directions) as in the reference workpiece parts presented in the Japanese Standards Association (JSA) [27] and Behrendt et al. [28] for studying energy demand of machine tools. The length of the milled slot was 70 *mm* (Figure 1). An 8 *mm* diameter 4 flutes short carbide coated end mill cutter was adopted for the cutting tests. A new cutter was used for the slot milling of each new toolpath orientation. This is done to reduce the influence of tool wear on the power demand during the milling tests. The cutting tests were conducted under dry cutting environment to prevent the power of the coolant pump from masking the cutting power, and also to promote sustainable machining. The air cutting and slot milling tests were repeated three times.

3. Results and discussions

3.1. Toolpath orientations and power demand of the feed axes

The measured feed axes power was obtained when the tool performed slot milling of AISI 1018 steel alloy at various toolpath angles of 0º, 15º, 30º, 45º, 60º, 75º and 90º and at feedrate of 500 *mm/min*. The power consumption of the spindle rotating at 4000 *rev/min* was measured as 3123.17 *W*. The feed axes air cutting power was deduced by subtracting the power demand of the spindle from the air cutting power. The same estimation was applicable to the total power demand during dry cutting operations. Figure 2 presents the feed axes power demand during air cutting and milling of slots as the tool executes linear toolpaths at different angles.

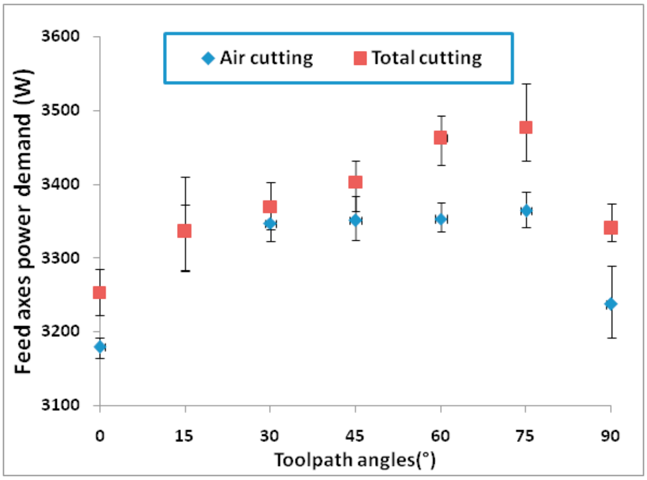

Fig. 2. Comparison of feed axes power for air and total cutting

Fig. 2 presents the minimum feed power demand during air and slots cutting was recorded at 0º while the highest power demand was at 75º (i.e. 3364 *W* and 3477 *W* for air cutting and cutting respectively). This is because movement of the feed drive at this angle is aligned with the x-axis direction which carries minimum weights. In considering Fig. 2, feed power demand was higher by 31% at toolpath orientation of 75º compared with the feed power required at 0º when machining at a feedrate of 500 *mm/min*. At 90º, the feed axis consumed 12% more electrical power than at 0°. Therefore, machining at 0° (i.e. when the toolpath is aligned in the x-axis direction) could save up to 31% feed power than machining at other angles.

Also from Figure 2, a sharp increase in feed power demand between 0° and 15° followed by a fairly steady increase in feed power demand as the toolpath angles increased from 15° to 75° is observed, while a decrease in power demand is seen between 75° and 90°. This may be due to the fact that feed power demand at 0° and 90° is minimal as a result of only one axis being actuated as tool movements are aligned along the x and y axes directions respectively. On the other hand, the feed axes power demand at toolpath angles between 15° and 75° is greater when compared with the feed axes power required at 0° and 90° due to the fact that two axes are activated, and the combined weights of the x and y axes motions result in higher feed axes power demand as the toolpath orientation tend to increase towards the heavier y axis. Hence, results from this study show that minimum power demand, and hence energy demand could be achieved on the Takisawa Mac-V3 milling machine when machining the length of the axis carrying less weight.

4. Conclusions

This work is aimed towards the development of a new framework that could be adopted to determine the optimal toolpath orientation, and to conduct a comparative study and individualization analysis of machine tool axes weights for electrical power consumption management in slot milling operations of AISI 1018 steel alloy. This is conducted to develop recommendations for the management of power consumption for green manufacture. The following conclusions can be drawn from the study:

- The optimum toolpath orientation for minimum feed axes power demand when machining AISI 1018 steel alloy are found to be 0° and 90°. It can be concluded that performing slot milling on AISI 1018 steel alloy at an angle aligned in the direction of the lighter axis (i.e. x-axis) resulted in minimum feed axes power demand .

- The feed axes power demand at toolpath angles between 15° and 75° is greater when compared with the feed axes power required at 0° and 90° as a result of the two axes being activated at the same time. Hence, the combined weights of the x- and y- axis motions result in higher electrical power demand.

- Since only one axis is being actuated as tool movements are aligned towards the directions of the x and y axes respectively, the feed power demand at 0° and 90° becomes minimal.

- Therefore, for green and sustainable machining of AISI 1018 steel alloy, it is recommended that the 0° and 90° toolpath orientations should be promoted. This would ensure minimum consumption of resources.

References

[1] Duflou, J.R., et al., Towards energy and resource efficient manufacturing: a processes and systems approach. CIRP Annals - Manufacturing Technology, 61, 587-609, 2012.

[2]. Balogun, V.A., I.F. Edem, and P.T. Mativenga, Specific energy based characterisation of tool wear in mechanical machining processes. International Journal of Scientific & Engineering Research,, 2015. 6(5).

[3]. Edem, I.F. and V.A. Balogun, Sustainability analyses of cutting edge radius on specific cutting energy and surface finish in side milling processes. International Journal of Advanced Manufacturing Technology, 2017.

[4]. Sreejith, P.S. and B.K.A. Ngoi, Dry machining: Machining of the future. Journal of Materials Processing Technology, 2000. 101: p. 287-291.

[5]. Fang, F., et al., Sustainable design and analysis of CNC machine tools: sustainable design index based approach and its application perspectives. Proceedings of the ASME 2016 International Manufacturing Science and Engineering Conference MSEC2016, Blacksburg, Virginia, USA MSEC2016-8730, 2016.

[6]. Park, C.-W., et al., Energy consumption reduction technology in manufacturing - A selective review of policies standards and research. International Journal of Precision Engineering and Manufacturing Vol. 10, No. 5, pp. 151-173, 2009.

[7]. Balogun, V.A., I.F. Edem, and P.T. and Mativenga, E-smart toolpath machining strategy for process planning. The International Journal of Advanced Manufacturing Technology, 2016.

[8]. Kyoto Protocol 1997, United Nations Framework Convention on Climate Change, Available from: http://unfccc.int/resource/docs/convkp/kpeng.pdf, Accessed on: 13 September, 2016.

[9]. EPTA 2007, Study for preparing the first working plan of the eco-design directive. Report for tender No. :ENTR/06/026.

[10].CECIMO 2009, Concept Description for CECIMO's Self-Regulatory Initiative (SRI) for the Sector Specific Implementation of the Directive 2005/32/EC, Available from: http://www.cecimo.eu/site/publications/magazine/cecimo-self-regulatory-initiative/, 2009. Accessed on: 13 September, 2016. .
[11].Kramer, T.R., Pocket milling with tool engagement detection. Journal of Manufacturing Systems, 1992. 11(2): p. 114-123.
[12] Edem, I.F. and V.A. Balogun, Energy efficiency analyses of toolpaths in a pocket milling process. IJE TRANSACTIONS B: Applications Vol. 31, No. 5, 847-855, 2018.
[13].Edem, I.F., V.A. Balogun, and P.T. Mativenga, An investigation on the impact of toolpath strategies and machine tool axes configurations on electrical energy demand in mechanical machining. International Journal of Advanced Manufacturing Technology, 2017. 92(5-8): p. 2503 - 2509.
[14].Smid, P., CNC Programming Handbook - A Comprehensive Guide to Practical CNC Programming. Third Edition, 2008: Industrial Press, Inc 989 Avenue of the Americas, New York, NY 10018, USA. 2008.
[15].Toh, C.K., A study of the effects of cutter path strategies and orientations in milling. Journal of Materials Processing Technology, Volume 152, Issue 3, Pages 346-356, 2004.
[16].Edem, I.F. and P.T. Mativenga, Energy demand reduction in milling based on component and toolpath orientations. Procedia Manufacturing 7 (2016) 253-261, International Conference on Sustainable Materials Processing and Manufacturing, SMPM 2017, 23-25 January 2017, Kruger National Park, 2016.
[17].Baptista, R. and J.F. Antune Simoes, Three and five axes milling of sculptured surcaces. Journal of Materials Processing Technology, 2000. 103: p. 398-403.
[18].Park, S.C. and B.K. Choi, Toolpath planning for direction-parallel area milling. Computer -Aided Design, 2000. 32: p. 17-25.
[19].Monreal, M. and C.A. Rodriguez, Influence of toolpath strategy on the cycle time of high-speed milling. Computer -Aided Design, 2003. 35(4): p. 395-401.
[20].Rangarajan, A. and D. Dornfeld, Efficient toolpaths and part orientation for face milling. CIRP Annals - Manufacturing Technology, 2004. 53(1): p. 73-76.
[21].He, Y., et al., Analysis and estimation of energy consumption for numerical control machining. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2011. 226(2): p. 255-266.
[22].Kong, D., et al., Software-based tool path evaluation for environmental sustainability. Journal of Manufacturing Systems, 2011. 30(4): p. 241-247.
[23].Edem, I.F. and P.T. Mativenga, Modelling of energy demand from computer numerical control (CNC) toolpaths. Journal of Cleaner Production, 2017. 157: p. 310 - 321.
[24].Edem, I.F. and P.T. Mativenga, Impact of feed axis on electrical energy demand in mechanical machining processes. Journal of Cleaner Production 137 (2016) 230-240, 2016.
[25].Edem, I.F., Energy modelling for machine tool axis and toolpaths, in A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy (PhD) in the School of Mechanical, Aerospace and Civil Engineering, Faculty of Science and Engineering. http://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.728178. 2017.
[26].ISO 14955-1:2014, ISO 14955-1:2014 Machine tools - environmental evaluation of machine tools - Part 1: Design methodology for energy-efficient machine tools.
[27].Japanese Standards Association, Machine Tools - Test Methods for Electric Power Consumption - Part 1: Machining Centres, TS B 0024-1:2010. 2010.
[28].Behrendt, T., A. Zein, and S. Min, Development of an energy consumption monitoring procedure for machine tools. CIRP Annals - Manufacturing Technology, 2012. 61(1): p. 43-46.