Tool Path optimization by Genetic algorithm for Energy Efficient Machining

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Abstract— The highly flexible CNC machines are used extensively by manufacturing industries for producing a variety of components. The cost of energy is about one fifth of the operating cost of these machines and this cost is increasing steadily. Many strategies are practiced to reduce energy consumption by these machines in order to lower manufacturing expenditures and also to minimize the carbon footprint. The feed drives share considerable amount of energy in the total power consumption of a CNC machine. In this research work, a tool path optimization method is presented to improve the energy efficiency of the machine. This is achieved by making use of the difference in energy requirement of the various feed drives. Genetic algorithm with modified cross over method was used for this purpose. The presented method was experimented analytically with a drilling problem to find an energy efficient path. An optimized tool path for minimum cycle time was also found and the two tool paths were compared in an energy perspective. Results show that the energy efficient tool path consumed less energy than the tool path optimized for minimum time. The proposed method can be adapted to CNC machines with multiple axis with interpolated movements to predict the minimum energy toolpaths.

Keywords— Tool path Optimization, CIM, Energy efficiency, TSP, Energy Modelling, Genetic algorithm

I. INTRODUCTION

Manufacturing processes are found to be energy intensive and the impact on environment by the carbon footprint left by them is high [1,2]. The rising cost of energy also is affecting the manufacturing industry economically. Hence the optimization of the electricity consumption at the production and process level stages of manufacturing is necessary. Researchers accept that performing an exclusive analysis of manufacturing processes to estimate overall energy demand is necessary[3]. For reducing energy demand of machine tools, it is essential to devise methods to characterize the energy consumption of manufacturing processes [4].

Most of the existing works on energy reduction in the manufacturing industry were focused on making energy efficient machining methods. Machine tools which are used in great numbers constitute substantial size of industrial energy consumers [5,6]. The reduction of energy consumption of machines may bring considerable reduction in the environmental impact of consumer products [7]. CNC machines are highly utilized machines for machining operations which require enormous electric power[8]. The ever increasing cost of energy and the release of greenhouse gases by fossil fuels necessitates researchers to minimize the use of energy by these machines [9]. The environmental impacts of CNC machines are mainly due to their electrical energy demand and CO2 emissions [10,11,12]. The efficient use of energy is an important problem, making the manufacturing industries continuously look for solutions. Energy efficiency of machine tools could be improved by identifying strategies for reducing its non-cutting energy demand [13]**.**The electrical energy consumed by these machines during the material removal process is dominated by the energy required for supporting the non-cutting operations, machine tool feed axes and auxiliary units[14]. The energy spent for non-cutting operations takes major share of the total energy consumption in machining [15]. This means that the machine consumes huge energy even during the non cutting tool movements because of the fixed energy requirements.

A. Tool path Optimization for productivity by minimum cycle time

Research works on toolpath optimization were mainly aimed at minimizing the time for metal cutting, minimizing the tool in air time, minimizing the tool change time and inspection time. Most research papers presented techniques for the optimization of machining parameters, tool selection and the type of toolpaths to be used [16]. Many researchers presented methods to optimize tool sequence to minimize the tool switch time [17,18]. Optimization algorithms with heuristic approach were used to arrive tool paths in metal cutting operations to minimize the non cutting tool time [19, 20]. Abu Qudeiri et al.[21] proposed a method to optimize the tool path for different operation processes that were located asymmetrically on more than one level, with a single cutting tool. Danijela Peter [22], compared the tool paths created by CAM software and by Genetic Algorithm. A Kumar et al.[23], optimized drilling tool paths using GA . Abu Qudeiri [24] solved The Traveling Salesman Problem (TSP) for two different arrival and departure points with constraints for tool collision. Alwis et al.[25] applied a row by row technique to sequence X axis and Y axis values of drill holes from minimum to maximum. Zlatan Car et al. [26], approximated the 2D surface with cells, and the tool has to travel in a minimum path with the lesser number of cells. Car et al. [27], created a Tool life model for the goal function and cutting force and power models represented constraint functions. Lim et al.[28], proposed hybrid cuckoo search-genetic algorithm (CSGA) for the optimization of hole-making operations in which a hole may require various tools to machine its final size with an objective to minimize the total non-cutting time of the machining process, including the tool positioning time and the tool switching time.

B. .Tool path optimization for sustainable manufacturing

Toolpaths are defined as the route through which the cutter machine the workpiece. By Optimizing the NC toolpath the efficiency of a milling process could be improved and sustainable machining could be achieved[29]. The authors emphasized the need for proper selection of tool path in order to save energy in machining processes. They presented a method for the prediction of the energy consumption by toolpaths based on NC codes. Proper choice of tool path planning can enhance the optimization possibilities during machining [30,31]. Machine tool feed drives control the relative motion between the workpiece and cutter, as well as determining the workpiece geometry [32]. Xie et al.[33] utilized an object oriented simulation approach to model the feed drive movements for achieving productivity. He et al. [34] considered the importance of feed rates in their feed axes power demand model while the weights of the axes, workpiece, and machine vice were not considered.

A new idea of intelligent orientation of work piece for energy efficiency based on feed axes weights is gaining importance recently. Many researchers took interest in creating solutions for minimizing energy consumption and discussions focused the work piece orientation on energy consumption. Kong et al. [35] investigated the machine tool axes along various orientations with results showing that maximum feed rate in the x-y plane of the machine axes occurs at 45 degree and machining of toolpaths in the x-axis direction resulted in minimum energy. The authors showed that an efficient cutting strategy can often result in substantial savings in energy to produce the same part feature with no loss of cycle time. They also discussed the different toolpath strategies in milling for their energy consumption and effects on the environment by introducing web-based application program interface. Their findings have indicated that the power consumption of toolpaths in x axis feed direction is lower than that of y axis and emphasized the need of optimized selection of toolpath for energy consumption. Diaz et al. [36] experimented with the energy required for different toolpath plans and found that the machining along the x-axis of the machine tool requires less energy in comparison with the y-axis due to the fact that the x axis drive is placed over the y-axis. The authors also noted that longer the toolpaths the consumed energy also more due to prolonged processing time. Vila et al. [37] experimented with different tool path layouts and their impacts on the specific energy demand and found that machining in x-axis direction was the most energy efficient with reduced CO_2 generation. Edem and Mativenga [14] experimentally found that toolpaths aligned to the lighter axis reduced the energy demand by 29%.

C. Motivation and aim of the present work

The literature about Tool path optimization studies give details about different techniques used to minimize the cycle time of a machining process in order to improve productivity. The energy requirement aspect was not considered while devising an optimization method by most of the authors. The tool paths generated by commercial CAM software have algorithms aimed at the shortest tool paths only and the minimum energy consumption function is not available in these programs. The literature about energy requirements of CNC machine has given insights about the energy consumption by various activities during machining. Some research works discussed the effect of structural configuration of machines and orientation of workpiece on energy consumption. From the literature it is learned that an energy efficient toolpath development method was not explicitly discussed. Although the influence of tool path on energy consumption has been pointed out further work on developing energy efficient tool paths has not been done yet. Since the optimization of drill tool path for energy efficiency was not discussed so far, this problem is considered in the present research work. The objective is to choose a tool path plan in which the lighter slide travels more than the energy consuming heavier axis.

II. OPTIMIZATION METHOD

A. Problem

To develop a CNC tool path plan to reduce electric power consumption by the feed drives. The work piece shown in fig 1. has a number of holes to be drilled for which the workpiece has to be moved in a path under the tool in such way that the overall power consumption for positioning the workpiece is minimum.

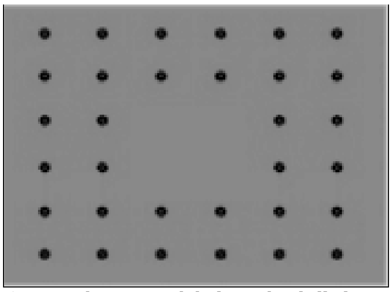


Fig.1 Work piece with holes to be drilled.

B. Solution procedure

The procedure of this research work is as follows.

1. CNC Machine configuration is analyzed to identify the mass moved by various feed drives of the machine.
2. A model representing the energy requirement of each drive is selected.
3. An optimization algorithm with required parameters is chosen for the problem.
4. The algorithm is tuned by running it for several trials.
5. The optimized tool path sequence is obtained.
6. CNC code is manually written using the sequence .

1) Configuration of CNC machining centre

In a basic configuration of a CNC machining centre, the machine has minimum three major axis x, y and z. Advanced CNC machines have more number of axis including the rotary axis a, b and c around the main axes for machining complex three dimensional shapes. The workpiece is clamped on a table and fed against the tool by the simultaneous movement of various axes moving at different feed rates. Figure 2 shows a 3 axis CNC machine in which the x axis slides over the guide way placed on Y axis. To translate workpiece in x axis direction the x axis slide is moved, while moving in y axis direction, the y axis slide is moved carrying the x axis slide along with it.

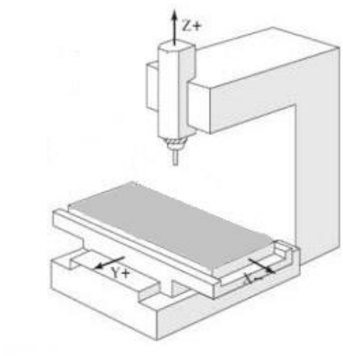


Fig.2 configuration of a typical CNC machine.

2) Effect of Feed direction in Energy consumption

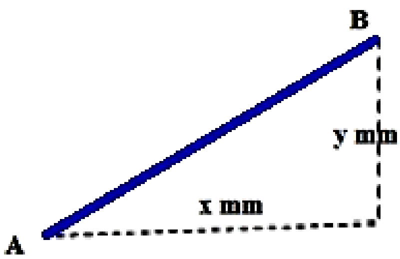


Fig 3. Moving from A to B achieved by moving x and y slides.

For moving the workpiece between any two points in x-y plane, both x and y feed drives are actuated. To move the workpiece from A to B as shown in Fig.3, x axis slide and y axis slide are moved simultaneously in an interpolated path for different lengths with different velocities.Figure 4 shows the different possible tool path plans and Table 1. shows the total individual distance moved by x and y slides.

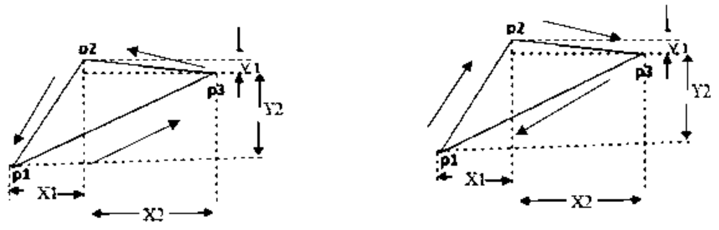


Fig. 4. Two different Routes for the drilling the holes p1.p2 and p3.

Table 1 X axis and Yaxis slide travel length for the two routes

		X distance	Y distance
Sequence 1	pt 1→ pt 2→ pt 3	x1 + x2	(y1+y2)+y1
Sequence 2	pt1→ pt3→ pt2	(x1+x2)+x2	y2 +y1

To move workpiece in x axis direction, the mass to be moved is the sum of the masses of work piece, work holding device and x axis slide. Similarly for moving the workpiece in y direction, the mass to be moved is the sum of the masses of y axis slide with x axis guide way, x axis slide and mass of workpiece with clamping device. It is evident that since y axis carrying the x axis also , moving the work piece in y direction requires more energy than moving in the x direction. Similarly the various feed axes slides of CNC machine with different configurations have different masses and the energy required to move them are different. The lighter axis consume less power than the heavier axis for sliding at any feed rate. Figure 5 shows a general feed drive arrangement of an axis in a CNC machine.

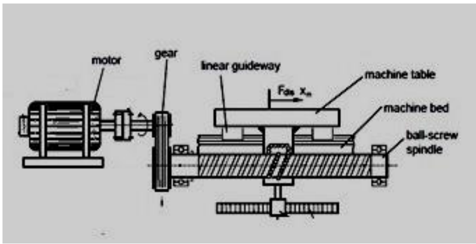


Fig.5 CNC Feed drive

To achieve energy efficiency for a given tool path plan the heavier slides must be moved for lesser distance than the lighter drives. Consider the three points p1, p2 and p3 in a drilling plan shown in fig2 which can be connected by six routes(with different start and end point) in two different sequences as shown in table 1. In sequence 2 distance travelled by y axis is less than that of x axis and hence the energy consumption in sequence 2 is less than that of sequence 1.With the help of an energy prediction model the power requirements of individual drives can be estimated.

3) Feed drive Electrical energy modelling

In CNC machines formulating an accurate energy model to predict energy demand precisely is very difficult. Energy models are developed by measuring the power consumption of feed axes in different conditions for a specific make and model of CNC machine. The energy consumption of different drives and equipments are measured in various cutting conditions at different speed and feed rates . Figure 6 shows the power measurement made for a CNC milling machine by moving x axis and y axis separately.

Fig.6 CNC Milling machine power measurement.

A number of researchers modeled many CNC machines and the results were fairly accurate enough for energy prediction. A detailed examination of the power requirements of individual components, possible savings can be predicted and procedures can be described for the efficient use of energy. Several research works present energy based models for the selection of optimized cutting parameters, and tools with Energy savings obtained up to 40% by these approaches [38,39]. Campatelli et al. [40] proposed to predict the energy consumption of Mori Seiki three-axis NV1500DCG machine with the following equation (1).

$$P = \int_0^s ((Mxa_x \ \ +\mu_x M_x g) + M_y a_y \ \ +\mu_y M_y g) ds \text{ -------(1)}$$

The Takisawa Mac-V3 milling machine is a three-axis, conventional-speed vertical milling machine with a direct current (DC) servo motor model 20M and spindle model A06B0652-B. The operations of the milling machine tool are controlled with FANUC controller. This machine is capable of spindle speeds up to 10,000 rev/min. The machine construction has the machine table and x-axis mounted directly on the y-axis, thereby increasing the load on they-axis than the x-axis as presented in Fig. 7.

Fig. 7 Takisawa Mac-V3 Milling machine

The masses for the x- and y-axes are approximately 315 and 750 kg, respectively [14]. The x-, y-, and z-axes accelerate at 10 m/s^2 with rated power requirements of 0.85 kW for the x- and y-axes, and 1.2 kW for the z-axis. The axis drives are powered by AC servo motors connected directly to the ball screw drive. Takisahawa machining center has an acceleration of 1g (10 m/sec^2). Since developing an energy model is not the objective of this work the modelling developed for the CNC machine *Takisawa Mac-V3* by Edem and Mativenga [14] was adapted* for this research work.
The model equations for x and y axis are shown in equations (2) and (3),

$$P_{fx} = P_o + (0.27\, Wv_f + 0.10\, W) \text{ --------- (2)}$$

$$P_{fy} = P_o + (0.91 Wv_f + 0.05W) \text{ -----------(3)}$$

The required power is a function of the mass and velocity of the feed drive. Equation (1), (2) and (3)are known as energy models. The friction factor is not included in these models since power consumed for friction was also observed while arriving these models. The velocity of the feed drives are different for various axes and jerk need not be be considered since the effect of it in choosing a tol path is minimum.

4) Solving TSP by Genetic Algorithm

Since the tool has to move to a number of locations in a machining plan, finding an optimum tool path among the numerous possibilities is considered as Travelling Salesman Problem. The tool path optimization to minimize the air time was treated as Traveling salesman problem (TSP) by many researchers [21]. In this research work the application of Genetic Algorithm is used to solve the TSP in MATLAB environment. The TSP is a combinatorial optimization problem in which a number of cities are visited by a salesman, each city is visited only once and all the cities are visited in a tour and it is referred as NP - hard problem. The best tool path can only be found by searching solutions in an exhaustive search space which is impractical in a polynomial time. By solving the TSP near perfect solutions are found by optimization techniques. The objective is to find the shortest tour path among the (n-1)! possible paths. If 'D' is the distance to be travelled by the salesman then the (4) where (5) is fitness function.

$$minimum\ D = \sum_{k-1}^{n} d(c_k, ck_{+1}) \text{-----------------------} (4)$$

$$d = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \text{--------------------} (5)$$

Genetic algorithms is an intelligent method to find approximate solutions to combinatorial optimization problems, D.E.Goldberg [41]. The basic parameters of GA are i) the crossover probability ii) the mutation probability iii) the population size and iv) the number of iterations, Melanie Mitchell[42]. Genetic algorithm is used to find approximate solutions to combinatorial optimization problems using the survival of the fittest concept. In GA the solutions are assumed initially and by repeated creation of improved population until satisfactory results are obtained.

C. Case study

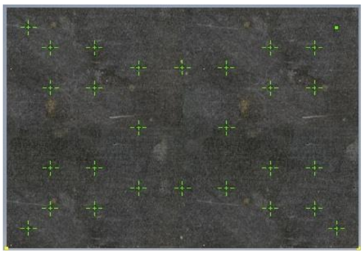


Fig 8.Work piece with 28 holes to be drilled

The proposed method was verified analytically with a drilling problem shown in Fig 8. The component shown has 28 number of drill holes of size 4 mm to be machined in a CNC milling machine for which an energy efficient tool path is to be selected. Total energy required to move work table between any two successive holes p_i and p_{i+1} is calculate by the following steps.

$$\begin{aligned}
&\text{mass of x axis slide} &&= m_1\ kg = 315\ kg \\
&\text{mass of y axis slide} &&= m_2\ Kg. = 750\ kg \\
&\text{Distance moved by the table} &&= d\ m. \\
&\text{velocity of Table} &&= v\ m/s = 5\ m/min \\
&\text{Time taken by the table} &&= d/v \\
& &&= t\ secs. \\
&\text{Time taken by x slide} &&= t\ secs. \\
&\text{Time taken by y slide} &&= t\ secs. \\
&\text{velocity of x slide } v_1 &&= (x_i - x_{i+1})/t\ \ m/s \\
& &&= x/t\ \ m/s \\
&\text{velocity of y slide } v_2 &&= (y_i - y_{i+1})/t\ \ m/s \\
& &&= y/t\ \ m/s \\
& P_x &&= (0.27\ Wv_f + 0.10\ W) \\
& P_y &&= (0.91 Wv_f + 0.05W) \\
&\text{Energy required by x slide} \quad E_x &&= P_x * t_x \\
&\text{Energy required by y slide} \quad E_y &&= P_y * t_y \\
&\text{Energy required to move the workpiece} \quad E_{total} &&= E_x + E_y \\
&\text{Energy required for the cycle} &&= \sum_{i=0}^{n} (Ex + Ey) \quad \text{---------} (6)
\end{aligned}$$

Equation (6) is the fitness function for the optimization algorithm . The experiments were performed on the Windows 7 operating system with Intel Dual-core CPU at 2.40GHz and 8.00GB of main memory. Genetic Algorithm was implemented in the Matlab R2016b scientific programme environment. The satisfying parameters for the GA was arrived after a number of trials with different alternative values for population and number of Iterations. The parameters of GA are shown in Table 3.

Table . 3 Parameters of GA

Parameters o GA	Values
Population size	1000
No of iteration	10000
No of Nodes	28
Cross Over fraction	0.5
Mutation fraction	0.08

III. Results and discussions

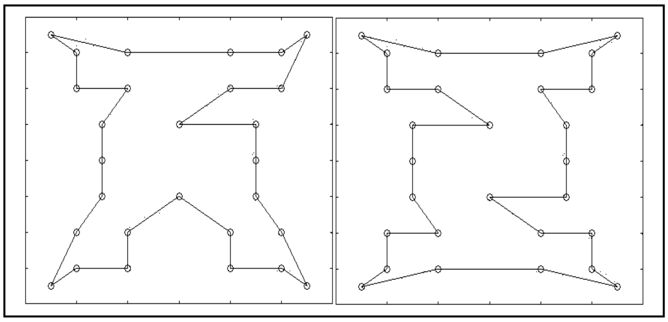
The energy efficient tool path for the drilling problem is given by the below tool path sequence The energy required to move the x and y feed axes at the feed rate of 5m per minute is 7.5 kw.

26 → 27→ 28 → 22 → 15 → 9 → 8 → 7 → 14 → 13 → 6 → 5 → 4 →11→ 3 → 2 → 1→ 10 → 16 → 23 → 24 →25 → 17 → 12 →18→ 19→ 20 → 21.

The tool path optimized for minimum cycle time for the same problem is given below.

20 → 13 → 21 → 26 →28 →27 →22 →15 →9 →8 → 7 → 14→ 6 →5 → 4 →3 → 1 → 2 → 10 →11 →12 →17 → 16 → 24 → 23 → 25 → 18 → 19

Figure 9 (a and b) shows the two tool paths selected by the two optimization methods and table 4 gives the comparison of the two methods . Since the chosen work piece is symmetric about x and y axis, the Energy efficient tool path has not given a considerable power savings than the optimized tool path for Minimum cycle time.



a). b).

Fig 9. a).Tool path optimized for minimum cycle time b). Energy efficient tool path

Table 4 . Comparison of two tool paths for symmetrically shaped workpiece.

Tool path Details	Tool path optimized for minimum cycle time	Tool path optimized for energy
Total Energy required	8074.6 watts	7876.4 watts
Length of tool path	624.99 mm	644.35 mm
X axis dist	360 mm	420 mm
y axis dist	380 mm	320 mm
energy x	2668.7 watts	2792.9 watts
energy y	5406 watts	5083.6 watts
Cycle Time	7.4999 sec	7.7322 sec

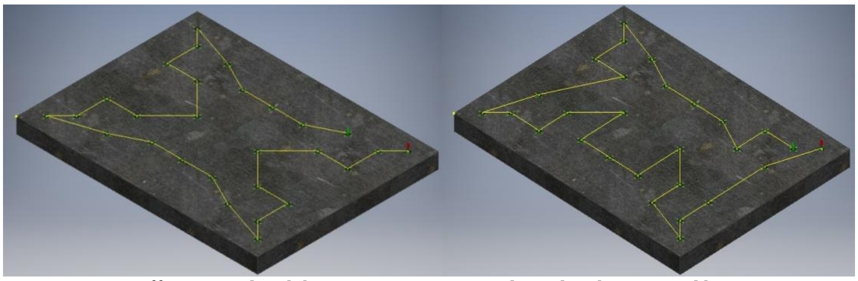


Fig 10. Energy efficient Tool path by GA optimization and Tool path optimized by CAM system.

Figure 10 , table 7 and table 8 present the comparison study of tool paths developed by Autodesk Inventor and optimization method presented in the present paper.The comparison table 8 shows the energy savings achieved by the optimization procedure. Power savings of 2749 watts was achieved by the optimaztion procedure over the tool path generated by Inventor. This was possible since the y axis slide movement was reduced by 240mm by the optimization algorithm.

Table 7 . Optimization results for the the two approach

Tool path Details	Inventor generated	GA optimized
Machining time	7,34minutes	7,32 minutes
Cutting time	7,11 minutes	7,11 minutes
Rapid time	20 secs	18 secs
Tool change time	3 secs	3 secs
Tool path length	1925.8575 mm	1804.0334 mm
Cutting length	280 mm	280 mm
Rapid length	1645.8575 mm	1524.0334 mm
Rapid rate	5000mm/min	5000mm/min
Feedrate	39mm/min	39mm/min

Table 8. comparison of tool paths by inventor and GA.

Tool path Details	Inventor tool path	GA optimized tool path
Energy	1.7037e+04 watts	1.4288e+04 watts
Energy x	5.5466e+03 watts	5.2562e+03 watts
Energy y	1.1491e+04 watts	9.0317e+03 watts
distance	1.3099e+03 mm	1.1880e+03 mm
x dist	700 mm	900 mm
y dist	820 mm	540 mm
time total	15.7183 sec	14.2564 sec

The study was conducted for a table velocity of 5meter per minutes. The energy requirement for the same tool path at different feed rates is shown in chart 1. State of art CNC machines have rapid feed rates up to 15.24 meters per minute and smaller CNC machines have very high rapid rates (with linear guide ways) above 38 meters per minute. Rapid traverse rate is an important CNC machine specification need to be considered when buying a CNC machine. Even though this detail is provided by the Machine manufacturer machine users ignorant about this specification and selecting machine with a higher rapid rate saves good amount of money on electric power costs.

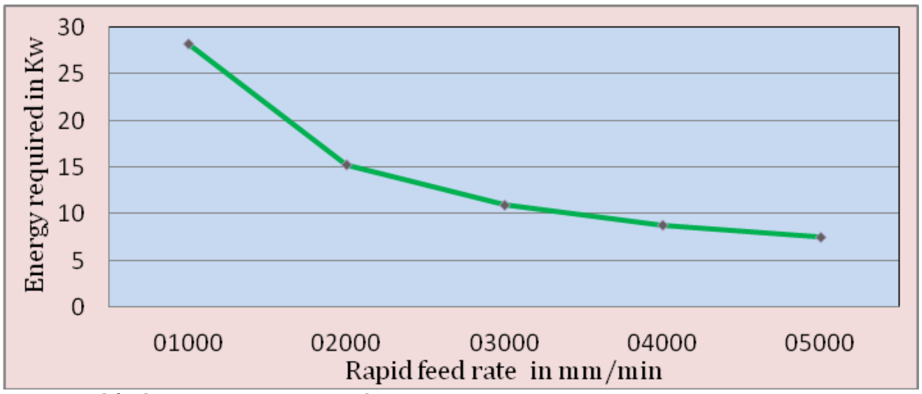


Chart 1: Rapid feed rate vs Energy required

IV. Conclusion

An energy efficient tool path optimization technique has been presented in this research work. In order to achieve this goal the feed drive with lighter weight was selected from the machine configuration and was made to travel more than the heavier axis with the aid of an optimization programme . The Takisawa CNC machine structure was selected for this purpose to find the drive with minimum mass .The method is applied to a drill hole problem to optimize the table movements for minimum energy consumption. The energy efficient tool path was developed by the application of GA. The developed tool path was compared with a tool path developed for minimum cycle time. It is found that tool path optimized with minimum energy objective consumes less energy than tool path optimized for minimum cycle time. A similar comparison was made with tool path developed by Mastercam. A CNC part programme was created using the developed tool path using Mastercam. The optimization work was done for non cutting tool path and as a continuation of this work, energy efficient tool path for machining operations will be developed. The method which is for two dimensional plan has to be enhanced for three dimensional tool paths by further work on this. The idle time minimized with an optimized tool path can also bring savings in the base power consumption which will be evaluated in further works. In future work improvisation of optimization algorithm will be done to speedier the problem solving time.

Acknowledgment

*The authors acknowledge the permission given by Professor Isuamfon F. Edem of Akwa Ibom state, Nigeria for allowing to use details from his research work.

References

[1]. N.Diaz ,N. Dornfeld and A.Horvath , "A comparative analysis of the environmental impacts of machine tool manufacturing facilities", Journal of Cleaner Production, 95: pp .223–231,2015.

[2]. C. W.Park et al., "Energy consumption reduction technology in manufacturing - A selective review of policies, standards, and research", International Journal of Precision Engineering and Manufacturing,10(5): pp. 151-173, 2009.

[3]. O.Avram, I.Stroud and P.Xirouchakis , "A multi-criteria decision method for sustainability assessment of the usephase of machine tool systems", International Journal of Advanced Manuf. Tech; 53:pp.811–828, 2011.

[4]. C.Herrman,L. Bergmann,S.Thiede and A. Zein, "Energy Labels for Production Machines – An Approach to Facilitate Energy Efficiency in Production Systems", Proceedings of 40th CIRP International Seminar on Manufacturing systems, Liverpool, UK. 2007.

[5]. Gardner business media, "World Machine-Tool Output and Consumption Survey", April 27, 2016.

[6]. A. Zein, "Transition Towards Energy Efficient Machine Tools", Springer-Verlag, Berlin Heidelberg; 2012.

[7]. A.Vijayaraghavan, and D.Dornfeld, "Automated energy monitoring of machine tools", CIRPAnnals - Manufacturing Technology, 59/1,pp. 21-24, 2010.

[8]. K.Fang, N. Uhan, and F. Zhao, "A new shop scheduling approach in support of sustainable manufacturing". Proceedings of the 18th CIRP international conference on life cycle engineering, Technische Universita¨ t Braunschweig, Braunschweig, Germany, 2–4 May 2011, pp. 305–310.

[9]. Jeswiet, J. and S. Kara, "Carbon emissions and CESTh' in manufacturing", C1RP Annals - Manufacturing Technology, 57,pp.17-20, 2008.

[10]. Lin, B. and X. Li, "The effect of carbon tax on per capita CO2 emissions". Energy Policy, 39,pp. 5137-5146,2011.

[11]. Ramseur, J.L., J.A. Leggett, and M.F. Sherlock, "Carbon Tax: Deficit Reduction and Other Considerations". Congressional Research Service, 2012.

[12]. W. Li, A. Zein, S. Kara, C. Herrmann, "An investigation into fixed energy consumption of machine tools", Proceedings of the 18th CIRP International Conference on Life Cycle engineering, pp.268-273, 2011.

[13]. Isuamfon F. Edem,Vincent A. Balogun and Paul T. Mativenga, "An investigation on the impact of toolpath strategies and machine tool axes configurations on electrical energy demand in mechanical machining". The International Journal of Advanced Manufacturing Technology, Volume 92, Issue 5–8, pp. 2503–2509, 2017.

[14]. Isuamfon F. Edem and Paul T. Mativenga, "Impact of feed axis on electrical energy demand in mechanical machining Processes", Journal of Cleaner Production ,137: pp.230–240, 2016.

[15]. Rajemi, M.F., and Paul T. Mativenga., "Machinability analysis from energy footprint considerations". Journal of Machine Engineering 8 (2),pp. 106–113, 2008.

[16] F. Kolahan and M. Liang, "Optimization of hole making operations: a Tabu-search approach," International Journal of Machine Tools & Manufacture, 40:pp. 1735-1753, 2000.

[17] A. Oral and M. C. Cakir, "Automated cutting tool selection and cutting tool sequence optimisation for rotational parts," Robotics and Computer-Integrated Manufacturing, 2004,20(2):pp.127-141.

[18] Y. Zhao, K. Ridgway, and A. M. A AI-Ahmari, "Integration of CAD and a cutting tool selection system," Computers & Industrial Engineering, 2002, 42(1): pp.17-34.C. Oysu and Z. Bingul, "Application of heuristic and hybrid-GASA algorithms to tool-path Optimization problem for minimizing airtime during machining," Engineering Applications of Artificial Intelligence, 2009, 22:pp. 389-396.

[19] K. Castelino, R. D'Souza and P. K. Wright, "Toolpath optimization for minimizing airtime during machining," Journal of Manufacturing Systems, 2002,22(3):pp. 173-183.

[20] Abu Qudeiri, J. Optimization of Operation Sequence in CNC Machine Tools Using Genetic Algorithm. Journal of Advanced Mechanical Design, Systems and Manufacturing, 2007,1(2):pp. 272-282.

[21] Danijela Peter, F., "Efficiency of Tool Path Optimization Using Genetic Algorithm in Relation to the Optimization Achieved with the CAM Software". Procedia Engineering, 2016,149: pp.374-379.

[22] Kumar and P.P. Pachauri, "Optimization Drilling Sequence by Genetic Algorithm. International Journal of Scientific and Research Publications", 2012, 2(9): pp.1-7.

[23] Abu Qudeiri, J., "Optimization and Program Generation of a Tool Path for Multi Cutting Tool Operations in CNC Machines". International Journal of Emerging Technology and Advanced Engineering, 2014,volume4, special issue 5, pp.15-23.

[24] Alwis, P.L.S.C., A.S. Premarathna, Y.P. Fonseka, S.M. Samarasinghe and J.V. Wijayakulasooriya, "Automated printed circuit board (PCB) drilling machine with efficient path planning". SAITM Research Symposium on Engineering Advancements. 2014.

[25] Zlatan Car, Tonci Mikac and Ivica Veza., Utilization of GA for optimization of Tool Path on a 2D surface. 2006.
[26] Car, Z., B. Barisic and M. Ikonic, "GA-based CNC Turning center Exploitation parameters optimization". METABK 2009,48(1): pp.47-50.
[27] Lim, W.C.E., G. Kanagaraj and S.G. Ponnambalam, "Hybrid cuckoo search-genetic algorithm for hole-making sequence optimization". Journal of Intelligent Manufacturing, 2016,27(2):pp. 417-429.
[28] Aramcharoen A and Mativenga PT, "Critical factors in energy demand modelling for CNC milling and impact of toolpath strategy" Journal of Cleaner Production, 2014, volume 78,pp.63–74.
[29] Guo Y, et al., "An operation-mode based simulation approach to enhance the energy conservation of machine tools", Journal of Cleaner Production 2015; 101: pp.348-359.
[30] Rangarajan A, Dornfeld D, "Efficient Tool Paths and Part Orientation for Face Milling", CIRP Annals -Manufacturing Technology, 2004; 53:pp. 73-76.
[31] Altintas, Y., "Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNCDesign",second edition. 2012.
[32] Xie, Y., €Ozdemir, D., Herfs,W., "Object-oriented modelling of machine tool feed axes: an approach to analysis of control parameters". In: Proceedings of 2015 IEEE International Conference on Mechatronics and Automation. August 2015 Beijing, China.
[33] He Y, Liu F, Wu T, Zhong F-P and Peng, B., "Analysis and estimation of energy consumption for numerical control machining". Proceedings of Institution of Mechanical Engineering Part B, Journal of Engg. Manufacture, 2011, 226(2):pp.255–266.
[34] Kong**,** D., Choi, S., Yasui, Y., Pavanaskar, S., Dornfeld, D., Wright, P., "Software-based tool path evaluation for environmental sustainability". Journal of Manufacturing Systems. 2011; 30: pp.241-247.
[35] Diaz N, et al "Machine tool design and operation strategies for green manufacturing". In: Proceedings of the 4th CIRP International Conference on High Performance Cutting. 2010.
[36] Vila, C., Abellán-Nebot J.V. and Siller-Carrillo H.R "Study of different cutting strategies for sustainable machining of hardened steels". Process Engg,2015, 132:pp.1120–1127.
[37] Calvanese, M.L., Albertelli, P., Matta, A., and Taisch, M., "Analysis of energy consumption in CNC machining centers and determination of optimal cutting conditions". In: 20th CIRP International Conference on Life Cycle Engineering, 2013. Singapore.
[38] Beno, T., Kara, S. andnAnderberg, S.E., "Impact of energy efficiency on computer numerically controlled machining". Proceedings of Institution of Mechanical Engineering Part B, Journal of Engg. Manufacture, 2010, 224(4):pp.531–541.
[39] G.Campatelli, A.Scippa, and L.Lorenzini , "Workpiece orientation and tooling selection to reduce the environmental impact of milling operations". 6th CIRP International Conference on High Performance Cutting. HPC2014, Procedia CIRP, vol 14, pp 575–580. 2014.
[40] D.E.Goldberg, Genetic Algorithms in search Optimization and Machine Learning, Addison-Wesley Publishing Company, Ind. U.S.A. 1989.
[41] Melanie Mitchell, An introduction to genetic Algorithm. MIT press, 1998.