Generation and Optimization of Pocket Milling Tool Paths - A Review

L.W. Kariuki, B.W. Ikua and G. N. Nyakoe

Abstract—The use of Computer Numerical Controlled (CNC) machines in manufacturing industry has led to the development and wide application of Computer Aided Design and Manufacturing (CAD/CAM) softwares. These software have the capability to generate important machining procedures and parameters, which include tool paths. Pocket milling, which involves the removal of all material inside a closed boundary makes use of CAM generated tool paths to remove material to a fixed depth. The efficiency of these CAM generated tool paths in carrying out various pocket milling operations has become an important subject of research, since more than 80% of all mechanical parts which are manufactured by milling machines can be cut by NC pocket milling.

Conventional tool paths were generated using CAM softwares to satisfy geometric requirement, and have been successful in achieving desired shapes of parts. However, physical conditions such as cutting forces and vibrations are not put into consideration. In addition, the reliance on operator’s intuition and experience to select from various CAM generated tool paths compromises limits achievement of technological aims such as good surface finish, minimal cutting forces, high Material Removal Rate and minimal machining time.

In this paper, a review on the work done in generating efficient tool paths, optimizing already existing tool paths strategies and optimizing the selection of tool paths during machining is presented. The impact of tool path on pocket milling process is drawn from the reviewed work.

Keywords—CNC, Optimization, Pocket milling, Tool path

I. INTRODUCTION

COMPUTER Numerical Controlled (CNC) machines have become very popular in modern manufacturing because of their ability to machine complex geometries with high dimensional accuracy. With the increasing need for unattended manufacturing, high productivity and high product quality, the use of CNC machines together with Computer Aided Manufacturing (CAM) softwares is becoming increasingly vital.

Nowadays the trend in Computer Aided Manufacturing (CAM) systems development is to make diverse CAM systems capable of recognizing the particular features which compose the 3D model of the part and then according to geometric shape recognition generate the most important machining procedure and parameters.

Pocket milling is the removal of material inside a closed boundary on a flat surface of a workpiece, to a fixed depth, using one or more milling cutters. It is also referred to as 2.5D machining since all the machining is done in one plane and that plane has a single depth in the third plane at each point. These pockets may have straight edges, curved edges or a combination of both, as shown in Figure 1. 2.5D machining is useful in that tool path control can be achieved easily and quickly, and a wide range of parts can be machined using this method. The tool axis in pocket milling is strictly fixed with respect to the workpiece, therefore only the direction of the milling feed can be considered. It is commonly applied in the manufacture of dies, molds and high-precision aerospace and car manufacturing components.

Fig. 1. Illustration of pocket milling operation

More than 80% of all mechanical parts which are manufactured by milling machines can be cut by CNC pocket machining [1]. This is due to the fact that many mechanical parts consist of faces parallel or normal to a single reference plane. Also, free-form objects can be produced from a block workpiece by carrying out 2.5D roughing (pocketing) and then 3D-5D finishing. The efficiency of a pocket milling tool path is therefore quite important in CAM, and thus, improvement of tool paths can have a widespread impact in the manufacturing industry.

II. POCKET MILLING TOOL PATHS

Tool path refers to a series of coordinate locations that a cutting tool follows in the machining process, to produce a certain geometry or part. Tool paths are significant in pocketing as they, together with process parameters and tool and workpiece properties, determine the productivity in a machining operation. Unlike in other milling operations, in pocketing there exists many tool paths strategies that can
achieve the desired profile, but at varying efficiencies. Two common tool path strategies are usually taken during pocket milling, namely, linear (direction parallel) and contour parallel tool paths. Linear tool-paths are generated parallel to a particular direction, as shown in Figure 2. They are of two major variations, namely, unidirectional and bidirectional linear tool paths. In unidirectional approach, the tool is retracted at the end of each cut in one direction, and is retraced to the start of the new pass without cutting on the return stroke. Tool retraction leads to a considerable amount of idle time, during retracting the tool and returning it to the start position. It also lengthens the machining path and could negatively affect the tool life. In bidirectional approach, the tool cuts both in the forward and the backward motion. The tool is not retracted at the end. As a result of minimal tool retractions, burr formation is avoided which occurs at the point of the tool leaving the workpiece while engaged.

![Contour-parallel tool path](image)

**Fig. 2.** Contour-parallel tool path

![Direction-parallel tool path](image)

**Fig. 3.** Direction-parallel tool path

Non-linear tool-paths comprise of two kinds of tool path, contour-parallel and parametric tool path strategies. Contour parallel tool paths, shown in Figure 3, are derived from the boundary of machining region, be it straight or curved. The tool path is generated by successive offset curves along the work boundary. The cutter is kept in contact with the work most of the time thus less idle time spent in retracting, positioning and plunging. It is widely used for large scale material removal.

Parametric tool paths are often used as a finishing tool path. These general tool path strategies have with time been modified to come up with new strategies, adding to the options a machinist encounters when generating a tool path. Modern CAM software provide up to eight tool path strategies to select from, when machining a simple rectangular pocket, as shown in Figure 4. This leaves wide room for improvement of tool path efficiency. For example, table axes on CNC milling machines may have different masses. Thus, movement in one direction may be more advantageous in terms of energy consumption. This means that it would be beneficial in tool path planning to have more movements in the advantageous axis, from the available alternatives. Also, acceleration and deceleration consume more energy than when the milling machine is moving at a constant velocity. Consequently, it is preferable to have longer paths and fewer stops during cutting [2].

![Tool path strategies available in Mastercam for rough milling of a pocket](image)

**Fig. 4.** Tool path strategies available in Mastercam for rough milling of a pocket

### III. OPTIMIZATION OF EXISTING TOOL PATH STRATEGIES

Optimization refers to a process of searching for the best solution in the space of possible solutions. In manufacturing, optimization can be carried out with various technological goals such as:

- achieving best possible surface quality
- minimizing tool wear
- achieving shortest machining time
- minimizing machining costs

Optimizing cutting tool paths is one of the ways to achieve the global trend of improving throughput and lowering cost of production in manufacturing industry.

With the continuing challenge in manufacturing to produce high quality products at the lowest cost, application of optimized tool paths is usually a missing link. The usefulness and efficiency of a CNC machining center is also dependent on the tool and the tool path applied during machining. The tool path has always been the weak link in the manufacturing chain, since it is rarely optimal. Optimization of tool path applied in manufacturing can increase productivity by as much as three times [3].

Conventional tool paths can be modified and even additional tool paths appended to the tool paths to achieve the optimal tool path. Other researchers have developed ways to select an optimal tool path from those available on a CAM system. Kim H. [4] presented an optimized tool path, which maintained Material Removal Rate (MRR) as constant as possible, so as to achieve constant cutting forces and to avoid chatter vibrations. In his work additional tool path segments were appended to the basic tool path obtained by geometric shape, using a pixel-based simulation technique. Both the geometry
and the tool are discretized and represented as pixel squares as shown in Figure 5.

![Pixel-based MRR simulation](image)

Fig. 5. Pixel-based MRR simulation

The algorithm was implemented for two-dimensional end milling operations, and cutting tests were carried out by measuring spindle current, which is proportional to MRR, to reflect the state of machining.

Pateloup et al [5], proposed a pocketing tool path improvement method that involved modification of the values of the corner radii in order to increase real feed rate. This method checked the radial depth of cut variations along the tool path. The computed tool path presented a smaller length and the machine tool produced a higher average feed rate at the same time, minimizing travel time thus meeting their optimization objective which was reduction of travel time. Use of B-splines for tool path computation was a notable improvement in this method, as compared to the use of straight lines and arcs.

Choy et al [6] suggested a corner-looping-based tool path for pocket milling. The basic pattern for the improved tool path was a conventional contour-parallel tool path. In their research they appended bow-like additional segments to the corner sections in the tool path, such that corner material was removed progressively in several passes, to prevent rise in cutting resistance. The proposed tool path was implemented as an add-on user function in a CAD/CAM system. Tests demonstrated that the improved tool path cleared accumulated material at pocket corners. The drawback presented by the improved tool path was longer cutter paths.

Yao et al [7] developed a tool path that combined different cutter path patterns, for different sections of the pocket. This was based on the observation that different tool path patterns were often efficient for certain types of pocket geometries, and yet for some complex pocket profiles, no single type of pattern produced efficient cutter paths throughout the pocket. Different tool path patterns were systematically analysed, and several existing heuristics for selecting cutter path patterns were discussed.

Based on observations, a new cutter path generation algorithm was described. The algorithm generated a cutter path by using different patterns in different regions of the geometry and seamlessly joining them together. In case of complex pockets, the developed algorithm produced solutions superior to those generated by any of the existing single patterns.

IV. TOOL PATH SELECTION

There exists a gap in the criteria that is used in selecting or generating the tool path to be applied in machining a pocket. By evaluating the quality and efficiency of the alternative solutions an optimal solution can be selected. In optimization of milling tool path, factors such as cutting-tool geometry and material, workpiece material, part geometry and use of coolants must be taken into account. Some of the approaches that have been applied in optimizing tool paths include reduction of machining time, minimization of cutting forces, modification of corner sections and avoiding redundant tool movements and potential collisions.

Neural networks have also been applied in optimizing tool paths, as described in the research by Korosec et al [8]. They demonstrated how with the help of artificial neural network, the prediction of milling tool path strategies could be performed in order to determine which tool path strategies or their sequence would yield the best results, since any machining task may be carried out using different tool-path strategies or sequences of various strategies. The result was that only one of all possible applied strategies was optimal in terms of the desired technological goal or aim. The study was based on production of car lights equipment by the tool shop industry. Their technological aim was to achieve the best possible surface quality of machined workpieces, which they verified by measuring surface roughness.

A. Energy consumption

Different pocketing tool path alternatives have different time and energy requirements. This leaves room for improvement in energy efficiency by selecting tool paths that minimize on energy consumption. Youngwook [2] based research findings on Micrography, a special type of calligraphy, to develop an algorithm to select pocketing tool path that minimizes energy consumption, since both processes are very similar. He observed that for CNC milling machines having different masses of table axes, movement in one direction would consume more energy than in the other direction. It would therefore be beneficial to have more movements, as much as possible, in the axis with lower moving masses. Also during acceleration from rest and deceleration, more energy is consumed, thus longer paths and fewer stops during cutting in a tool path plan is beneficial.

B. Number of tool retractions

Tang et al. [9] presented an algorithm based on zigzag milling to minimize the number of tool retractions for a pocket with holes and islands. The aim of the algorithm was to find the optimum inclination of the sweep lines and the minimum number of partitions required for the pocket to be machined. The partitioning was then done in such a way that no tool retraction was required within a sub-region. The partitioning was restricted such that it was parallel to the scan lines.
number of partitions for a pocket depended on the pocket geometry and the sweep angle. For a given sweep angle, there were several configurations in which a pocket could be divided. Each configuration was considered separately and some were ruled out, as they were not minimum.

Sang et al [10] carried out a study on Contour-parallel offset (CPO) machining, which uses successive offsets of the boundary curves of the pocket as the tool path elements. For CPO machining to be efficient the number of tool retractions must be minimized, since they cause additional tool movements without contributing to actual machining. They developed an algorithm that guaranteed zero tool retractions. The algorithm employed a concept called TPE-net, which provides information on relationship of parent-child segments. From this a route is planned through the TPE-net to generating a CPO tool path without tool retractions.

C. Machining time

In an experimental study carried out by Jayswal and Taufik [11], two strategies were investigated for reduction in machining time. The main objective of this work was to get a cutting strategies for cutting time optimization in CNC end milling operations. The first strategy communicated with Mastercam software by optimization of tool path using CAD/CAM simulation. The second strategy required selection of optimal cutting parameters for pocket milling process. Machining parameters were investigated in order to minimize the cyclic time and to improve the machining operation in terms of cost and time. Effects of selected parameters on process variables, which in their case were spindle speed, depth of cut, feed and stepover, were investigated by using Taguchi method and response surface methodology (RSM). Conclusions drawn from this study were firstly, that a zigzag tool path is more favorable than any other strategy for the rough machining of pocket in terms of cycle time and the tool-workpiece contact duration. Also, depth of cut was found to be the most significant factor affecting cycle time, followed by feed. Stepover had a small influence while spindle speed had insignificant influence on the cycle time. Response surface methodology was found to be an effective tool to develop the mathematical model to predict the optimum value of cycle time for a set of input parameters values within the experimental domain.

Daneshmand et al [12] investigated the numerous tool paths available in two common CAD/CAM softwares, CATIA and Mastercam, so as to determine the most suitable tool path. This was done for the roughening operation of machining a gearbox model and a disc screen, using both end mill and ball-nosed tools. They simulated the tool-path planning strategies according to the machining time provided by the software. The accuracy of the operations verified the most suitable tool path. Their research results indicated that for Mastercam, the minimum machining time was achieved with zig-zag strategy when using end mill, and spiral strategy when using ball-end tool. For CATIA, the back and forth strategy gave the minimum machining time when using end mill and inward helical strategy when using ball-nose tool. They also found that machining time changes when the geometry of the object being machined was altered.

El-Midany et al. [13] developed a feed rate-machining time model that took into account machine acceleration and deceleration for automatically identifying the most productive tool path pattern. The model was then used to compare the total machining time for five common types of tool path patterns, namely, normal zigzag, smooth zigzag, normal spiral, smooth spiral and fishtail spiral. The results showed that the optimal tool path pattern was dependent on part geometry, physical characteristic of cutting tool and cutting conditions.

Another study based on machining time involved development of a machining time model to compare machining efficiency of four tool paths often applied in manufacture of dies and molds. These included three variations of the direction-parallel tool path, namely one-way path, pure zig-zag path and smooth zig-zag path, and the contour-parallel tool path. The model that Kim and Choi [14] developed and applied put to consideration the effects of acceleration and deceleration during machining. According to the data shown in Figure 6, the smooth zig-zag was found to be the most efficient regardless of the feedrate and path intervals used. This was attributed to the inserted smooth path segments that were almost free of accelerating and decelerating.

Fig. 6. Graph showing mean machining times for various tool paths [14]

D. Minimizing deflection forces, and consequently, errors

Another approach that has been applied in selection of milling paths for complex surfaces is minimizing of dimensional errors due to tool deflection, which was presented by Lopez de Lacalle et al [15]. This resulted in an improvement on the accuracy of milled surfaces. It was based on the calculation of the minimum cutting force component, which was related to the tool deflection. In the first suggestion, a general tool path direction was selected that minimized the mean value of the tool deflection force on the surface. Based on this the CAM operator could then produce a CNC program which lead to an accuracy improvement. The second option was to create a grid of control points and select different milling directions at each control point. Joining these points, the minimum force lines were defined on the workpiece surface and used as the master guides for the tool path programming of a complete surface. After applying these methods to 3-axis milling the dimensional errors reduced significantly.
E. Maintaining constant cutting forces and chatter avoidance

Cutting forces at the point of contact between the cutting tool and the workpiece affect the occurrence of chatter vibrations and consequently, the tool life and the surface finish. In pocket milling, these forces vary along the tool path as a result of changing inclinations and speeds, such as when cutting corners. Tool paths generated by CAM softwares are mostly geometrically feasible but seldom put to consideration physical process concerns like cutting forces and chatter vibrations.

In an effort to cope with this limitation, [4] introduced and verified an optimized tool path, which ensures that a Material Removal Rate (MRR) as constant as possible is maintained. This results in constant cutting forces and chatter vibrations are avoided to a great extent.

To achieve this, additional tool path segments were appended to the basic tool path obtained by geometric shape. A pixel-based simulation technique was implemented. To verify the effectiveness of the proposed method the algorithm was implemented for two-dimensional contiguous end milling operations, and cutting tests were conducted by measuring spindle current to reflect machining situations.

F. Avoiding redundant tool movements and potential collisions

Choi et al [16] proposed a method focused on avoiding redundant tool movements and potential collisions in multi-material layered manufacturing (MMLM) of heterogeneous prototypes. The approach facilitated control of MMLM and increased the fabrication efficiency of complex objects by generating multi-tool paths that avoid redundant tool movements and potential collisions. They used a topological hierarchy-sorting algorithm to group complex multi-material contours into groups connected by a parent-and-child relationship. The multi-tool paths generated enabled sequential deposition of materials without redundant tool movements. The build time was further reduced by another tool path planning algorithm that generated collision-free multi-tool paths to control the tools that deposit materials concurrently.

V. Conclusion

Tool paths are an important factor in CNC machining, and more so in pocket milling operations. Conventional CAM software tool path design raises many issues, which poses a disadvantage in CNC machining processes, as has been observed in this review. It can be drawn from this review that machining time, energy consumption, length of cutter path, number of tool retractions, cutting forces, chatter vibrations, deflection forces and dimensional errors are all influenced by the tool path generated for the machining of a pocket.

Without a greater understanding on design of tool paths and greater tool path optimization, there will be gaps in maximizing the usefulness of CAM software in CNC machining. Research on CNC machining operations in relation to the tool paths designed in CAM softwares is one practical way of bridging the gap and achieving the global goal of faster, less costly and more efficient machining. The efficiency in use of tool paths can be improved by integration of developed optimization models in CAM software.

This review is part of an ongoing research on optimizing of pocket milling tool paths based on force and chatter prediction models.

ACKNOWLEDGMENT

This work has been supported by Jomo Kenyatta University of Agriculture and Technology. The authors would like to thank members of the Department of Mechatronic Engineering and the Department of Mechanical Engineering, JKUAT, for their invaluable contribution to this work.

REFERENCES