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Efficient CNC Milling by Adjusting Material Removal Rate

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***Abstract*—**This paper describes a combined mathematical-graphical approach for optimum tool path planning in order to improve machining efficiency. A methodology has been used that stabilizes machining operations by adjusting material removal rate in pocket milling operations while keeping cutting forces within limits. This increases the life of cutting tool and reduces the risk of tool breakage, machining vibration, and chatter. Case studies reveal the fact that application of this approach could result in a slight increase of machining time, however, a considerable reduction of tooling cost, machining vibration, noise and chatter can be achieved in addition to producing a better surface finish.

***Keywords*—**CNC machines, milling, optimization, removal rate.

I. Introduction

SINCE the advent of computer-numerical control (CNC) machines significant improvements have been made in automatic tool path generation for machining operations. Today many integrated computer-aided design and manufacturing (CAD/CAM) systems are available capable of generating machining tool path for various operations, however, most of them still suffer from the need for significant user intervention [1]–[3]. In addition, these systems often do not generate optimum tool paths and consequently chatter and reduced tool life are common issues in CNC machining operations.

In the milling process there are several gaps to be bridged in order to push the envelope of modeling, simulation and optimization to the required level of generality, reliability and accuracy. Fig. 1 identifies these gaps in three main areas as (1) modeling of the geometric aspect of the process; (2) modeling of the physical aspect of the process; and (3) optimization of the process. On the other hand, additional gaps that need to be bridged to bring the work to the required level of practicality to allow for a rapid and effective implementation of the technology include the development platform and integration requirements for a typical machining set-up [3].

There have been many publications in the literature on improving machining efficiency when CNC machining is involved and Chandrasekaran et al [4] provides a comprehensive literature review. Afifi *et al.* [5] developed a computer-aided optimization package for the minimization of the residence time of a multi-component pallet being manufactured in a machining centre with a multi-tool facility.

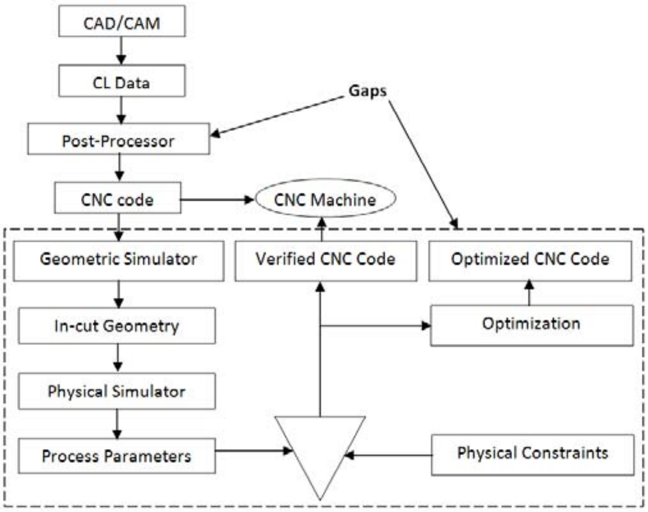

Fig. 1 Current gaps to bridge for a CAD/CAM and optimized CNC machining [3]

They developed a methodology to take a part program for the manufacture of many components which involves many tool changes, segment it, automatically re-sequence the machining order and regenerate it. It has been reported that the use of the computer-aided optimization package reduced the pallet residence time. In another work Song *et al.* [1] used a three-dimensional solid modeling system for automatic generation of optimum tool path for machining free-form surfaces on CNC machines. There are other works reported in the literature on optimization of CNC machining processes including [5] – [8]. Although these systems improve productivity of the CNC machining processes but these often do not address the optimization of material removal rate in pocket milling processes, leaving room for further investigation in this area.

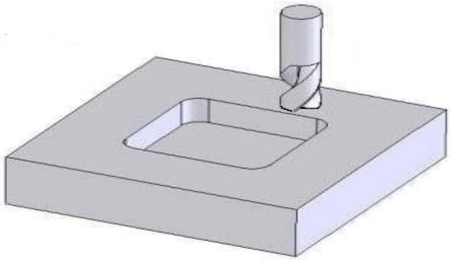

Fig. 2 A simple pocket milling operation

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II. POCKET MILLING

Pocket milling is frequently used in machining mechanical components particularly in producing industrial dies and molds. Fig. 2 shows a simple pocket milling operation where an end milling cutter is used for removing all the material inside a rectangular closed boundary on a flat surface of the workpiece to a fixed depth. Such a shape is frequently called a depression or a simple pocket.

As pocket milling is a very common operation in CNC milling there are many algorithms available for tool path generation of this operation [10] – [16]. However, often the algorithms presented only focus on geometric considerations and disregard other factors such as applied cutting forces and chatter that have a direct bearing on the stability of the machining operation and tool life.

The literature on controlling cutting forces and machining stability in particular case of pocket milling can be roughly divided into two major approaches: (1) feedrate scheduling and (2) tool path modification. The first approach focuses on controlling the cutting forces by adjusting the feedrate so it does not exceed the reference cutting force and is based on a cutting force model [17], [18]. If the model that predicts the cutting forces is exact, constant cutting forces can be achieved. Although cutting forces can be predicted exactly, it is impossible to keep the radial depth of cut or tool engagement angle constant using feedrate scheduling without tool path modifications. An example of such condition is shown in Fig. 3. The radial engagement of the cutter increases when the cutter moves into the corner region while it remains constant for straight path segments. As a result, a momentary rise in the cutting forces and chatter are commonly encountered that increase the cutting force and chatter and reduce the tool life.

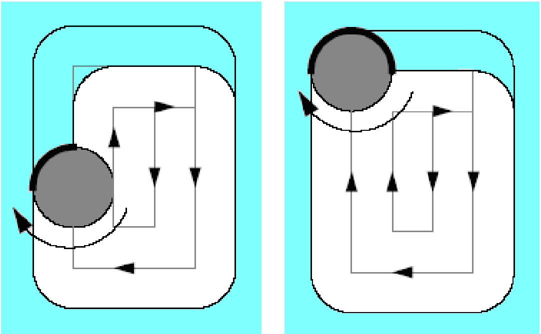


Fig. 3 Varying radial tool engagement in pocket milling

Consequently, modifying the tool path geometry becomes necessary for generating an optimal tool path and increased tool life. For example, in cutting pocket corners it is more effective to use additional tool paths to control the radial tool engagement. This paper describes an approach for optimum tool path generation for pocket milling operations considering applied cutting forces. This approach can be used in most common pocket milling operations.

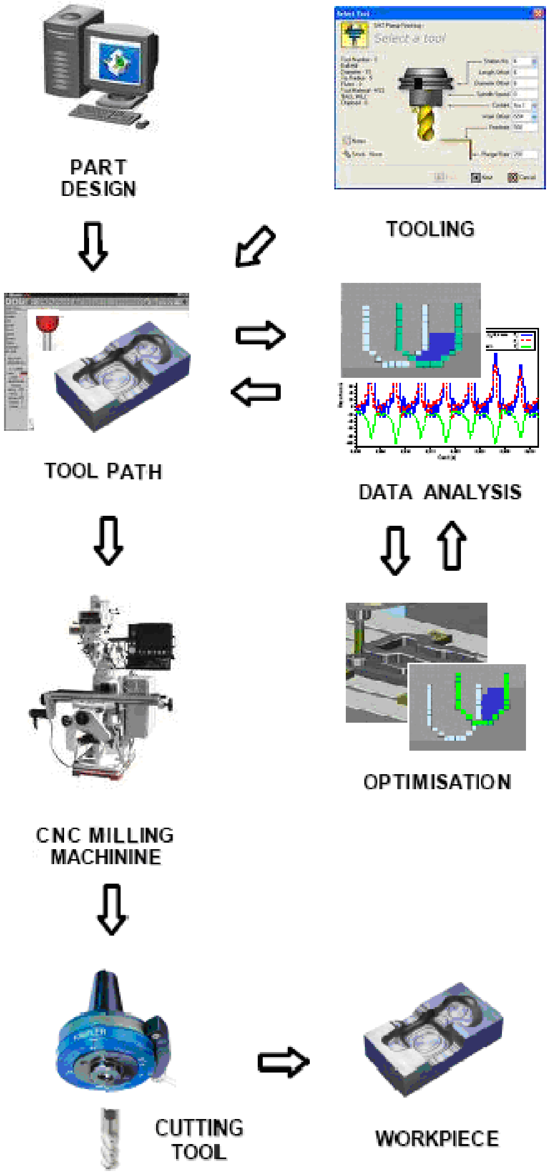


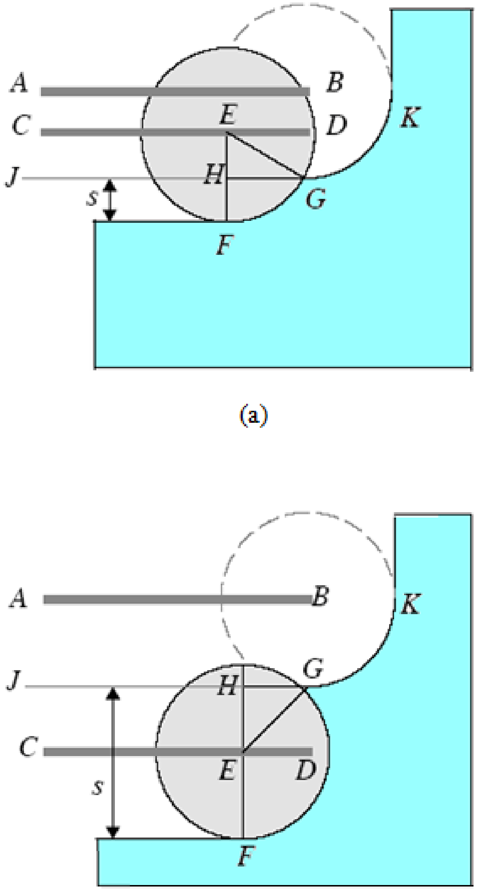
Fig. 4 System architecture for optimum tool path generation

III. SYSTEM ARCHITECTURE

Fig. 4 illustrates the architecture of the system proposed. Upon completion of part design on a computer-aided design (CAD) system the design is transferred to the computer-aided manufacturing (CAM) system for processing. This is followed by selection of proper cutting tools and machining parameters, and generation of the initial machining tool path using the algorithms present in the system. The cutter location (CL) data are then analyzed by a complementary data analysis module developed. If the analyzer detects any momentary increase of material removal rate in the machining process, the initial tool path is then modified by an optimization module programmed in C++. This is accomplished by use of a graphical-mathematical method developed that will be described in the next section. Once the optimized tool path is verified by data analysis module, it is transferred to the postprocessor for generating a CNC code that will be transferred to the CNC machine to cut the workpiece material.

IV. Optimum Tool Path

For an optimum tool path in a pocket milling operation, both the cutting forces and the radial tool engagement must be maintained at constant values over the entire tool path to ensure machining stability. This can only be achieved when the rate of material removal from the workpiece is maintained constant. For simplicity let us first consider a simple pocket milling operation with fixed axial depth as shown in Fig. 2. Fig. 5 (a) shows the top view of a milling operation where the material is being cut from left to right along the line *CD* by an end milling cutter, after having been cut previously along the line *AB*. The center of the tool has reached a point E where the point, *G*, of the first contact of the tool with the boundary of existing material has come to the end of a straight portion of boundary, *JG*, and started to lie on the arc *GK*. In Fig. 5 (a) the stepover, *s*, is less than the tool radius, *r*, whereas in Fig. 5 (b) the stepover is larger than the tool radius.



(a)

(b)

Fig. 5 Material being cut from left to right [14]

Kramer [14] presented an algorithm for generating a tool path for cutting a pocket with islands, which includes detecting when the tool is certain to be making a minimal engagement cut. A similar approach has been adapted here. The circle shown in dashed line in Fig. 5 shows the outline of the tool when its center was at *B*, so it may be seen why arc *GK* exists. Since the material along the line *AB* has already been cut, line *CD* is marked clear. However, it may be seen from the figures that as the center of the tool moves to the right of E, the radial tool engagement angle with material, *FG*, will increase beyond minimal engagement as contact point *G* moves up the arc *GK*. Therefore it becomes necessary to find the length of *ED*, which is the amount by which the clear portion of line *CD* should be shortened. It is observed first that *ED* is equal to *HG*. The value of *HG* can be found by using the Pythagorean Theorem on triangle *EHG*.

$$(HG)^2 = (EG)^2 - (EH)^2 \tag{1}$$

In Fig 5 (a), $EH = EF - HF = r - s$, whereas $EG = r$. Thus,

$$(ED)^2 = r^2 - (r - s)^2 \tag{2}$$

$$ED = (2rs - s^2)^{1/2} \tag{3}$$

In Fig 5 (b), $EH = HF - EF = s - r$,

$$(ED)^2 = r^2 - (s - r)^2 \tag{4}$$

$$ED = (2rs - s^2)^{1/2} \tag{5}$$

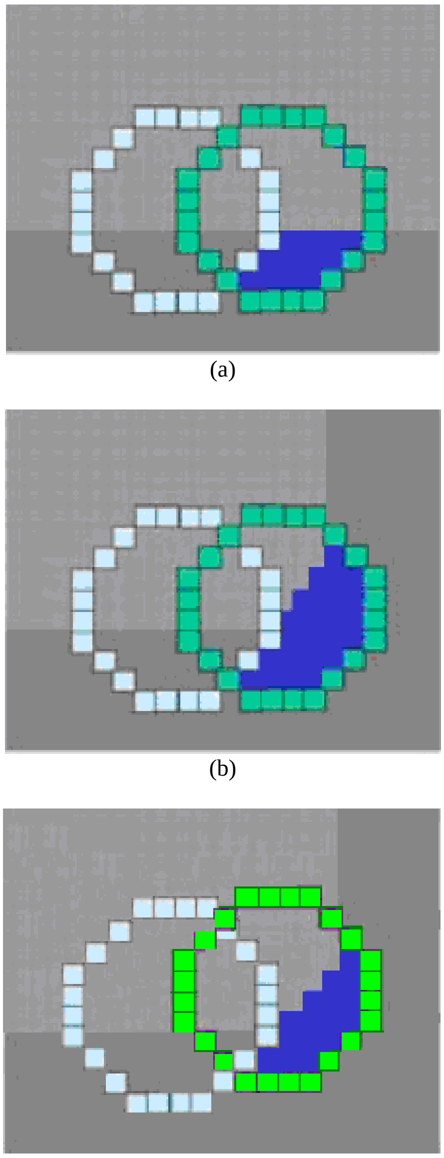
Therefore the tool path for the current path is kept at a length, *d*, shorter than the previous path in order to maintain constant material removal rate. Consequently as each cutting path becomes a distance, *ED*, shorter than the previous path, as shown in Figure 6 (a) an irregular pocket is concluded leaving much material for subsequent machining operations. Obviously this is not desirable. Yet another approach is employed as the cutting tool moves forward to bring the pocket shape closer to a regular shape, as shown in Fig. 6 (b). Obviously this shape is more desirable and the approach is described in the next section.

(a) *(b)*

Fig. 6 (a) The irregular-shape pocket wall formed by applying distance *ED* on each tool path, (b) the desirable regular shaped pocket wall

V. SIMULATION OF MATERIAL REMOVAL PROCESS

Fig. 7 illustrates the 2D pixel-based representation of the pocket milling operation. Both the workpiece material and the cutting tool are represented as discrete pixel squares. The dark gray region represents the material left to be machined and the light gray region has already been machined. The material removal rate is to be determined from the pixel numbers in the blue region. The reference pixel numbers representing nominal material removal rate at a given feed rate and for an increment of tool movement is determined by the number of pixels in the blue region when machining a straight segment of the cutting path.


(a)

(b)

(c)

Fig. 7 Graphical tool path optimization (radial)

As shown in Fig. 7 (a) there are 12 pixels in the blue region when machining the straight segment of the tool path. Therefore the reference pixel number for the given 2D image is 12. The material removal rate and resultant cutting forces are kept constant as long as the number of pixels in the blue region does not change for any increment of tool movement. Fig. 7 (b) illustrates the same cutting tool when machining the end of its straight path. Although the feed rate is kept constant the number of pixels in the blue region exceeds the reference number and reaches to 22. This would significantly increase the resultant cutting forces and chatter and reduce tool life. The tool path is thus modified in this region to avoid excessive material removal rate and to maintain the cutting forces within the acceptable range. Accordingly, as shown in Fig. 7 (c) the algorithm diverts the tool motion direction towards inside pocket such that the number of pixels in the blue region is maintained at or near to 12. It is noteworthy that for each increment of tool movement any number of pixels within the specified tolerance range, that is ±2 pixels for this particular case, is acceptable.Figs. 8 (a) (b) and (c) represent 2D pixel-based axial views of the cutting tool and the material. However, instead of a flat end milling cutter used for simple pocket milling operations, a ball end milling cutter is represented that is often used for contour shape milling and finishing operations. As seen in Fig. 7 (a), the reference pixel number in the blue region is 20 for any increment of tool movement. However, when the cutting tool encounters any protrusion or depression in its path, the number of pixels in the blue region is changed. For example, Fig. 8 (b) shows an increase in the number of pixels in the blue region to 28 due to the cutting tool encountering a protrusion in its course of moving forward. Again, the algorithm diverts the cutting tool towards outside the workpiece material in order to bring the number of pixels in the blue region within an acceptable range that is 21 for this particular case as shown in Fig. 8 (c).In the case of 2.5 axes machining the material removal rate is calculated by multiplying the number of pixels in the two views explained above:

$$r_f = n_1 \times n_2 \qquad (6)$$

where r_f represents the material removal rate (or volume) for any increment of tool movement at a feed rate of f, and n_1 and n_2 respectively represent the number of pixels in two intersecting directions or views. Similarly, for 3, 4 and 5 axis machining operations the proper volumetric computations should be applied depending upon the geometry of the machining feature and the cutting tool.

VI. CONCLUSION

The system proposed for optimum tool path planning in this paper improves the performance of the pocket milling operations via a combined mathematical-graphical approach.

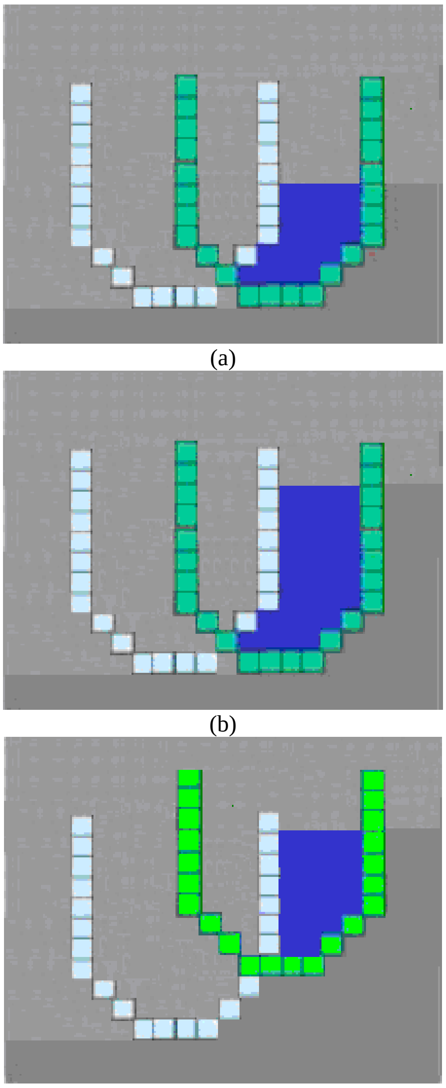

(a)
(b)
(c)

Fig. 8 Graphical tool path optimization (axial)

The improvement is achieved by maintaining material removal rate and resultant cutting forces and chatter within limits, and eliminating shocks on the cutting tool. This increases tool life and reduces the risk of tool breakage. Results have been verified by practical experiments during which smoother surface finishes and noticeable reduction in machining vibration and noise have been observed. This is in addition to approximately 15% increase of the tool life and achieving more stable and safer machining operations. However, machining time has slightly increased due to reduction of average material removal rate and longer tool paths. It is intended to extend the research in order to cover a wider range of milling operations particularly when machining sculptured surfaces requiring a 5-axis CNC machine. Initial experiments show that the same principle can be applied to these operations.

REFERENCES

[1] L. Song, S. K. Cao, K. Feng Song, C. Z. Wu, and W. W. Song, “Software Module Development for Free-Form Surface Five-Axis Machining Path and Tool Posture Simultaneous Optimization”, *Applied Mechanics and Materials,* vol.55-57, 2011, pp.1932-1937.

[2] M. Tolouei-Rad, “An approach towards fully integration of CAD and CAM technologies,” *Journal of Achievements in Materials and Manufacturing Engineering,* vol. 18, 2006, pp. 31-36.

[3] H. El-Mounayri, H. Kishawy, and V. Tandon, “Optimized CNC end-milling: a practical approach,” *International Journal of Computer Integrated Manufacturing,* vol. 15, 2002, pp. 453-470.

[4] M. Chandrasekaran, M. Muralidhar, C. Murali Krishna and U. S. Dixit, "Application of soft computing techniques in machining performance prediction and optimization: a literature review," *International Journal of Advanced Manufacturing Technology,* vol. 46, 2010, pp. 445-464.

[5] A. A. Afifi, D. R. Hayhurst, and W. A. Khan, “ Non-productive tool path optimization of multi-tool part programs,” *International Journal of Advanced Manufacturing Technology,* vol. 55, no. 9-12, 2011, pp. 1007-1023.

[6] C. H. Chu, C. T. Lee, K. W. Tien and C.J. Ting, “Efficient tool path planning for 5-axis flank milling of ruled surfaces using ant colony system algorithms,” *International Journal of Production Research,* vol. 49, 2011, pp. 1557-1574.

[7] Z. C. Wei, M. J. Wang, J. N. Zhu and L. Y. Gu, “Cutting force prediction in ball end milling of sculptured surface with Z-level contouring tool path,” *International Journal of Machine Tools and Manufacture,* vol. 51, 2011, pp. 428-432.

[8] J. K. Rai, D. Brand, M. Slama and P. Xirouchakis, “Optimal selection of cutting parameters in multi-tool milling operations using a genetic algorithm,” *International Journal of Production Research,* vol. 49, no. 10, 2011, pp. 3045-3068.

[9] X. F. Zhao, X. L. Liu, D.K. Jia and K. Ding, “Ball-end milling force modeling and simulation based on cutting path optimization experiments,” *Advanced Materials Research,* vol. 188, no. 9-12, 2011, pp. 348-351.

[10] Choy, H. S. and Chan, K. W., “A corner-looping based tool path for pocket milling,” *Computer-Aided Design,* vol. 35, 2003, pp. 155-166.

[11] Z. Yao and S.K. Gupta, “Cutter path generation for 2.5D milling by combining multiple different cutting path patterns,“ *International Journal of Production Research,* vol. 41, 2004, pp. 2141-2161.

[12] H. C. Kim and M. Y. Yang, “An optimum 2.5D contour parallel tool path,” *International Journal of Precision Engineering and Manufacturing,* vol. 8, 2007, pp. 16-20.

[13] H. S. Choy and K.W. Chan, “A corner-looping based tool path for pocket milling,” *Computer-Aided Design,* vol. 35, 2003, pp. 155-166.

[14] T. Kramer, *Pocket milling with tool engagement detection,* SME Publication, Product ID: JS92WBD2, 1992.

[15] E. Budaka and A. Tekelia, “Selection of axial and radial depth of cut pairs,“ *CIRP Annals - Manufacturing Technology,* vol. 54, 2005, pp. 353-356.

[16] M. Rauch and J. Y. Hascoet, “Rough pocket milling with trochoidal and plunging strategies,” *International Journal of Machining and Machinability of Materials,* vol. 2, 2007, pp. 161-175.

[17] M. Tolouei-Rad and I. M. Bidhendi, “On the optimization of machining parameters for milling operations,” *International Journal of Machine Tools & Manufacture,* vol. 37, 1997, pp. 1-16.

[18] S. H. Bae, K. Ko, B. H. Kim and B. K. Choi, “Automatic feedrate adjustment for pocket machining,” *Computer-Aided Design,* vol. 35, 2003, pp. 495-500.

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