Optimal Tool Path Generation for 2 ½ D Milling of Dies and Molds

Hui Li
Automotive Components Division
Ford Motor Company, *Dearborn, MI, USA*

Zuomin Dong (zdong@me.uvic.ca) and Geoffrey W. Vickers
Department of Mechanical Engineering
University of Victoria, *Victoria, BC, Canada V8W3P6*

Key words: sculptured part rough machining, 2 ½ D milling, CAD/CAM.

Abstract: Sculptured parts are usually produced through 2 ½ D rough machining and 3D-5D finish machining. The 2 ½ D, or contour map, rough machining plays a major role in removing excess material of the stock to form the parts. Improvement of this process can significantly increase the productivity of die and mold manufacturing. In this work, a number of algorithms were introduced to reduce the machining time of 2 1/2 D roughing. These include a new representation of various cutting layers, a method of tool path generation and planning for parallel and stock-offset milling. A simulation example is used to demonstrate advantages of the new approach.

1. INTRODUCTION

Free-form surfaces are widely used in complex dies and molds due to their functional and aesthetic properties. The machining of dies and molds involves a number of computer-aided approaches at various stages of production to solve problems ranging over surface modeling, process planning, tool path generation, machining monitoring, etc. [1]. Among these problems, tool path generation is especially important and has been investigated extensively [2]-[9]. Nevertheless, there are still a number of important issues need to be resolved.

It has been noted that a large number of mechanical parts are of an inherent 2 1/2 D nature, and complicated parts are usually produced in two phases: 2 1/2 D roughing and 3D-5D finishing. Based on several statistics, nearly 80 percent of all mechanical parts can be cut by using 2 ½ D milling. Thus the productivity improvement of the 2 ½ D roughing is very significant to industry.

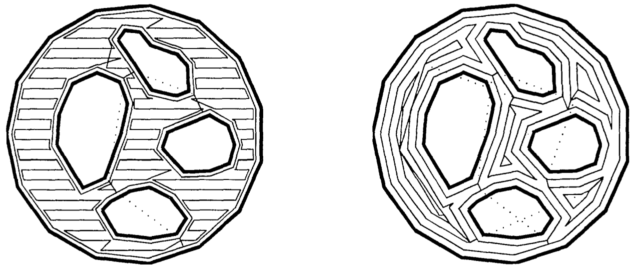
In 2 1/2 D roughing or *contour-map* roughing, cutter moves in certain predefined style or tool path pattern. *Parallel* and *stock-offset* are two most commonly used tool path patterns in practice. Following *parallel* tool path pattern, the cutter moves along a number of equidistantly spaced parallel lines in either unidirectional or bi-directional patterns as illustrated in Fig. 1 (a). In the case of using *stock-offset* tool path pattern, the cutter moves along a series of offset loops generated from the contours of stock and island as illustrated in Fig. 1 (b). The same example shown in Fig. 1 will be used throughout the paper to demonstrate the proposed approach.

In the authors' previous work, an extensive research on various feasible tool path patterns and identification of the optimal tool path pattern was carried out [6,7]. The study covered six feasible tool path patterns, including (a) stock offset, (b) component offset, (c) stack/component offset, (d) parallel offset, (e) proportional blending offset, and (f) max-min offset. For a cutting layer with a single island, the efficiency of these tool path patterns varies according to the shape of the part and stock. The equivalent length of its tool path or the total machining time measures the efficiency of each tool path pattern. A method for grouping cutting layers and identifying the most efficient tool path pattern for each group was

The original version of this chapter was revised: The copyright line was incorrect. This has been corrected. The Erratum to this chapter is available at DOI: 10.1007/978-0-387-35392-0_40

G. J. Olling et al. (eds.), *Machining Impossible Shapes*

introduced. In this work, we consider cutting layers with multiple islands. Due to the complexity of the cutting layer shape, we consider two most commonly used tool path patterns, *parallel* and *stock-offset*, as alternative tool path patterns.



(a) Parallel tool path pattern (b) Stock-offset tool path pattern

Figure 1 .Tool path patterns of 2 ½ D milling

2. OUTLINE OF THE APPROACH

An overview of the proposed procedure of *contour-map* machining is illustrated by the flow chart shown in Fig. 2. The input to the system includes the stock and part surface models, $F_s(x,y,z)$ and $F_p(x,y,z)$, the number of cutting layers N_c, cutter diameter d, the overlap ratios α_1 and α_2 of *parallel*

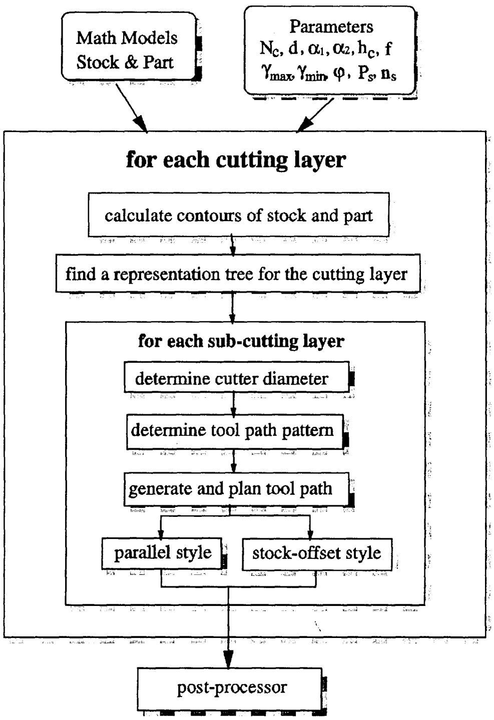
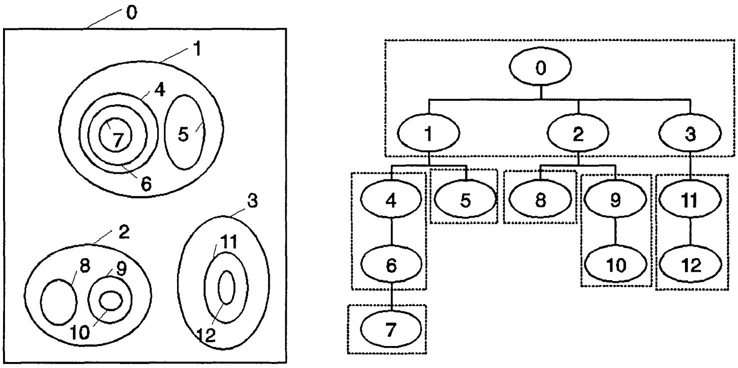


Figure 2. The Proposed Approach for Machining Dies and Molds

and *stock-offset* milling respectively, ramp parameters (r_{max} - maximum length of ramp, r_{min} - minimum length of ramp, and φ - angle of ramp), clearance level h_c, start cutting point p_s, and machining parameters (spindle speed n_s and feed rate f). For each cutting layer, contours of stock and islands are first generated by the intersection between a hunt plane passing though current cutting layer and surface models of stock and part as shown in Fig. 3 (a). These contours are then sorted to form a tree representing the topology of cutting layer. In the tree, each parent node in a level and its child nodes in the next level form a sub-cutting layer with restriction that each node can be treated only once, i.e. it can only be either a parent node or a child node, as illustrated in Fig. 3 (b). Next, an optimal tool path pattern is identified based on the shape of the cutting layer shape and cutter diameter. Tool path is then derived from the selected tool path pattern. Retractions, rapid traverse and ramps are added to connect sub-cutting layer with its next sub-cutting layer and, cutting layer with its next cutting layer. Finally, a post-processor is applied to generate NC machine code for cutting.



(a) A example of cutting layer **(b) Presentation tree of the cutting layer**

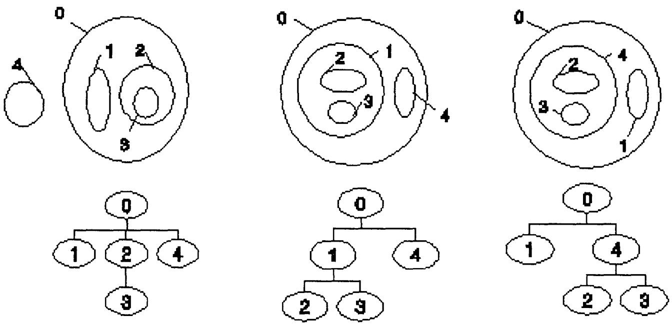
Figure 3. Representation tree of a cutting layer

3. CONSTRUCTION OF REPRESENTATION TREE

Representation Tree is referred to the topological structure of the cutting region in a cutting layer. Since multiple nested islands might exist for a general case as shown in Fig. 3 (a), a proper representation scheme is necessary to quickly find the geometry of sub-cutting layer. As discussed in previous sections, the cutting layer is specified by the contours, the intersection curves between a hunting plane at different levels and surface models of stock and part $F_s(x,y,z)$ and $F_p(x,y,z)$. $F_s(x,y,z)$ could be either a closed composite surface or a cylindrical surface generated by sweeping method. $F_p(x,y,z)$ could be either a closed composite surface, or an open composite surface extracted from the designed part. The contours of the stock are always a close curve, while the contours of the part can contain a number of open curves.

To construct the representation tree for a cutting layer, the stock contour, a close loop is put on the root, each loop in part contours is treated as a child node somewhere blew the root. If part contours contain open curves, these open curves are oriented so that the region that represents the projection of the part surface is staying on the right hand side of them. New islands are formed from those parts of the open curves that are enclosed in the stock contour. There are three cases of inserting a node in a representation tree, a stand-alone island; a protrusion or cavity inside a island; and a protrusion or cavity that contains islands, as illustrated in Fig. 4 (a)-(c).

The representation tree built for the example given in Fig. 3 (a) is shown in Fig. 3 (b). The root node 0 represents the stock contour, and other nodes represent part contours. All the sub-cutting layers are indicated by enclosing dashed boxes.



(a) Case 0 (b) Case 1 (c) Case 2

Figure 4. Three Cases of Inserting Node in Representation Tree

4. TOOL PATH GENERATION AND PLANNING

In the proposed method, tool path is basically generated in two steps: (1) creating cutter's trajectories for each sub-layer using proper tool path patterns, (2) connecting these trajectories with either cutting or non-cutting (travelling) movements. Ideally, tool path should be formed by connecting the cutter trajectories continuously without non-cutting moves. However, this is often impossible for the cases with complex contours or islands. Hence, it is necessary to plan the tool path, i.e. to sort the cutter trajectories and to connect them by fast traveling moves to reduce the machining time.

4.1 Generating Tool Path with *Parallel* Pattern

The proposed strategy for generating tool path of *parallel* milling is aimed at handling cutting layers with arbitrary shapes of stock and island contours. Using this strategy, the *parallel* tool path generation is completed in six steps:

1) Generate cutter trajectories denoted by *B_path* to clear the boundaries of stock and islands.
2) Calculate all the local extreme points on *B_path.*
3) Decompose the machining area enclosed by *B_path* into series of groups and construct a group graph, which indicates the connection among these groups. Two groups are assumed to be connected if they are adjacent in cutter's step-over direction and intersect with either stock or the same island contour on left or right side or on both sides.
4) Merge groups that are connected and intersect with the same contours on the both sides.
5) Generate parallel cutter trajectories and classify them into the above groups.
6) Starting from the top group, search along the group graph to find the next connected groups. Pick up the group that has minimum length of traveling move from the previous group and add it to the tool path. If no connected group is found, pick up a group that has not been processed in the graph and add it to the tool path with proper traveling move. Repeat this process until all the groups in the graph have been put into tool path.

The process of *parallel* tool path generation is illustrated in Fig. 5.

4.2 Generating Tool Path with *Stock-offset* Pattern

An approach of *stock-offset* tool path generation is presented herein. Cutting starts from the stock contour and goes inward to the island contours. The cutter trajectories *S_path* and *I_path* for clearing the boundaries of stock and islands are calculated first. If *S_path* and *I_path* have no intersection, add *S_path* to the tool path and let the curve that is the offset of the stock contour with a predefined offset distance to be the new stock contour. Otherwise, the intersection of *S_path* and *I_path* divides the cutting layer into a number of loops. The offsets of the loops within the cutting area are taken as the new stock contours. The tool paths of the sub-cutting layers formed by the new stock contours and islands contained in them are then generated recursively.

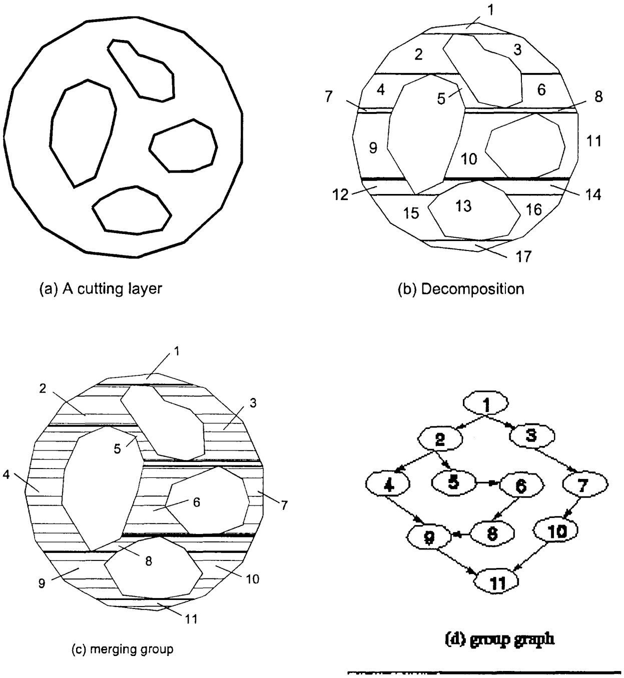


Figure 5. Tool path generation using *parallel* pattern

4.2 Generating Tool Path with *Stock-offset* Pattern

An approach of *stock-offset* tool path generation is presented herein. Cutting starts from the stock contour and goes inward to the island contours. The cutter trajectories *S_path* and *I_path* for clearing the boundaries of stock and islands are calculated first. If *S_path* and *I_path* have no intersection, add *S_path* to the tool path and let the curve that is the offset of the stock contour with a predefined offset distance to be the new stock contour. Otherwise, the intersection of *S_path* and *I_path* divides the cutting layer into a number of loops. The offsets of the loops within the cutting area are taken as the new stock contours. The tool paths of the sub-cutting layers formed by the new stock contours and islands contained in them are then generated recursively.

4.3 Selection of the Optimal Tool Path Pattern

The performance, in terms of productivity measured by cutting time or the total tool path length, of various tool path patterns has been studied by Wang, *et al.* [9], Held [4] and Li *et al.*

[6]. It has been found that tool path pattern has significant influence on tool path length or machining time. The influence is dependent on the shape and size of the stock and island contours, and the size of cutter used.

To select a proper tool path pattern, a basic criterion is to choose a pattern which results in less machining time. The machining time is composed of time spent on cutting material and time spent on travel in the air. Tool path of cutting movement contributes to the cutting time and tool path of travelling movement contributes to non-cutting (or traveling) time. The traveling time is mainly controlled by the shapes of stock and island contours, and the cutting area and cutter size are the major factors to influence the cutting time. Based on statistic result of examination of tool paths generated for various cutting layers, tool traveling time is usually a very small part of the total machining time (<2%). Hence, cutting time contributes most to the total machining time.

5. EXAMPLES AND DISCUSSION

The proposed approach has been tested by a number of examples of free-form surfaces. An example is a free-form protrusion part shown in Fig. 6 (a). Fourteen cutting layers are selected for rough machining of this part. Contours of these cutting layers are shown in Fig. 6 (b). The simulation results of machining time and selected tool path pattern are given in Table 1. In this simulation, feed rate is fixed at 300 *mm/min*; overlap ratios α_1 and α_2 for *parallel* and *stock-offset* patterns are chosen to be 0.9 and 0.7; cutter diameter used is 3/4".

The simulation result shows the influence of tool path pattern on total machining time. All the comparisons in the table are made with respect to the case using the best tool path pattern. The machining time increase is 4.51% and 1.73%, respectively. The result of the case with the tool path pattern selected by the proposed approach is very close to the best case.

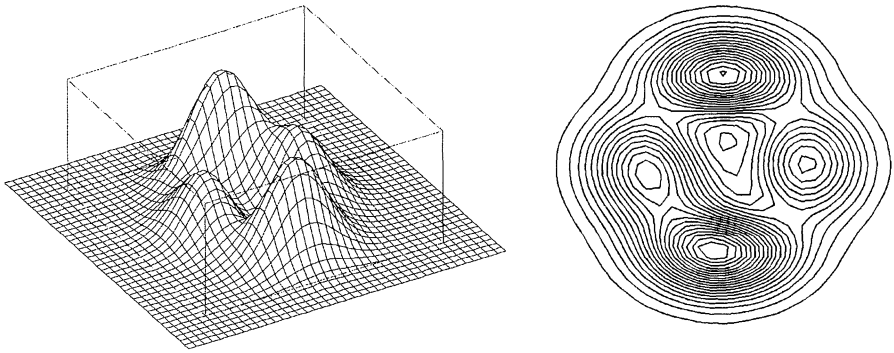
The proposed approach can be further improved by incorporating milling process model into it to maintain the chip load at desired level, in other words, to maintain a desired material removing rate during machining. This can be achieved by varying the feed rate according to the immersion geometry between the cutter and the workpiece. A milling process model is used for this purpose [6].

Table 1: Simulation Results

Cutting layer	*Stock-offset* pattern	*Parallel* pattern	Best pattern	Selected pattern
1	17.68	15.99	15.99	15.99
2	17.79	16.33	16.33	16.33
3	18.59	17.38	17.38	17.38
4	18.56	17.30	17.30	17.30
5	18.08	17.21	17.21	17.21
6	18.15	17.33	17.33	17.33
7	18.29	16.74	16.74	16.74
8	18.34	17.33	17.33	17.33
9	17.46	17.29	17.29	17.29
10	16.99	16.89	16.89	16.89
11	15.77	16.62	15.77	16.62
12	14.23	14.51	14.23	14.51
13	12.68	13.92	12.68	12.68
14	11.83	13.33	11.83	11.83
Sum	234.44	228.18	224.31	225.44
Comparison	4.51%	1.73%	0%	0.50%

ACKNOWLEDGEMENTS

Financial support from the Natural Sciences and Engineering Research Council (NSERC) of Canada is gratefully acknowledged.
The authors would also like to express their sincere appreciation to Professor R. Du of Department of Industrial Engineering at the University of Windsor, the Manufacturing Research Corporation of Ontario, and Reko Tool \& Mold Inc. for their inputs on the die and mold machining problems.



(a) A example of free-form surface

(b) Contours of the surface

Figure 6. An Example

REFERENCES

[1] Chang, T. C., Wysk, R.A. and Wang, H. (1991) *Computer-Aided Manufacturing*, Prentice-Hall, Inc.

[2] Guyder, M. K. (1990) "Automating the Optimization of 2 ½ Axis Milling," *Computers in Industry*, Vol. 15, pp. 163-168.

[3] Hansen, A. (1992). "An Algorithm for Generating NC Tool Paths for Arbitrarily Shaped Pockets with Islands," *ACM Transactions on Graphics*, Vol. 11, No.2, pp. 152-182.

[4] Held, Martin (1991) *On the Computational Geometry of Pocket Machining*, Springer-Verlag, Berlin.

[5] Lee, Y. S., Choi, B. K. and Chang, T. C. (1991) "Cut Distribution and Cutter Selection for Sculptured Surface Cavity Machining," *Int. J. Prod. Res.*, Vol. 30, No. 6, pp. 1447-1470.

[6] Li, H., Dong, Z. and Vickers, G. W. (1993) "Intelligent Rough Machining of Sculptured Part - Planning and Programming," in *Artificial Intelligence in Optimal Design and Manufacturing*, Prentice-Hall, Inc. pp. 235-258.

[7] Li, H., Dong, Z. and Vickers, G. W. (1994) "Optimal Toolpath Pattern Identification for Single Island, Sculptured Part Rough Machining Using Fuzzy Pattern Analysis," *Computer-Aided Design*, Vol. 26, No. 11, 1994, pp. 787-795.

[8] Suh, Y. S. and Lee, K. (1990) "NC Milling Tool Path Generation for Arbitrary Pockets Defined by Sculptured Surfaces," *Computer-Aided Design*, Vol. 22, No. 5, pp.274-284.

[9] Wang, H., Chang, H., Wysk, R.A., and Chandawarkar, A. (1987). "On the Efficiency of NC Tool Path Planning for Face Milling Operation," *Journal of Engineering for Industry*, Transactions of the ASME, Vol. 109, pp. 370-376.