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OPTIMAL TOOL PATH MODELING IN CONTOUR MILLING PROCESS

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Abstract: *In the design of CNC metal cutting technology, the tool path in contour milling is usually adjusted to technology form of the modeled work piece and contour to be processed, which satisfies the geometric criterion, that is the simplest in the choice of tool path. In this tool path selection, other criteria in terms of cutting forces, tool wear intensity, maximum depth, maximum cutting speed and desired surface quality, which are crucial for the productivity and efficiency of machining processes, are neglected.*
This paper presents the analysis of influencing factors on tool path choice in contour milling including phenomenological appearance in the cutting zone to identify the possibility of determining the optimal tool path. Among other things, an overview of the opportunities offered by modern CAM systems in generating NC code, which solves the problem of the tool path selection in contour milling, is given here.

Key words*: cutting process, contour milling, tool path, CNC technology*

1. INTRODUCTION

One of the most common operations in machining metal parts is pocket milling: removing all the material inside some arbitrary closed boundary on a flat surface of a work piece to a fixed depth [1].
In High Speed Milling (HSM), the spindle rotation speeds as well as the feed rates are much higher than for the conventional milling with an objective to minimize the manufacturing time without decreasing the part quality. In this paper, generation and optimization of tool paths for pocket machining is analyzed for High speed milling.
One of the pocket-machining paradigms changed by high-speed machining is that machine dynamics can be ignored when a tool path is generated. Conventionally, dynamics have been pretty much ignored; the best path was the shortest, and it either reflected the part pocket boundary shape in its entirety so-called parallel-offset paths or consisted of many straight-line segments zig-zag or raster scan. [2].

2. POCKET MILLING

Most of mechanical parts consist of faces parallel or normal to a single plane and free form objects require a 2.5D rough milling operation of the raw work piece, making 2.5 D pocketing one of the most important milling operations. Almost 80% of the milling operations to produce mechanical parts are produced by NC pocket milling [3].
In usual pocket milling using flat end milling tool, the pocket is generated by sweeping a cylindrical tool inside the pocket boundary. The rotating tool sweeps the material to be removed in its feed direction along a set of lines, circles and splines, which are usually referred as tool paths [3].

2.1. NC tool paths

NC tool paths can be classified into two major types, namely linear and non-linear. Examples of simple and easy-to-generate linear tool path are the zig and the zig-zag tool paths as shown in
Fig. *1* (a) and (b). The zig path is a uni-directional cutting path, and hence a consistent up-cut or down-cut chip removal method can be maintained. However, there is a considerable amount of non-productive time involved in returning the cutter to the start-cut position at the end of each cutting path. On the other hand, the zig-zag path is a bi-directional cutting path in which material is removed both in the forward and backward paths. Although the zig-zag tool path can reduce non-productive tool positioning time, it has the disadvantage that the up-cut and down-cut methods are alternately applied. This will lead to problems such as machine chatter and shorter tool life [4].

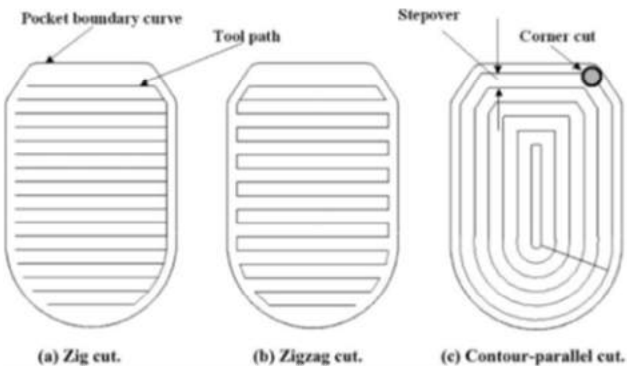


Fig. 1. Three commonly used tool path patterns. (a) Zig cut; (b) zig-zag cut; and (c) contour-parallel cut [4]

Parametric-based tool path is frequently used as a finishing tool path for machining parametric surfaces as the tool path is driven directly along the *u–v* parametric curves of the surface itself. As shown in Fig. 1(c), contour-parallel tool path pattern is derived from the boundary of the concerned machining region. It is a coherent tool path in the sense that the cutter is kept in contact with the cutting material most of the time. So it incurs less idle times such as those spent in lifting, positioning and plunging the cutter. At the same time it can also maintain the consistent use of either up-cut or down-cut method throughout the cutting process. Contour-parallel tool path is therefore widely used as a cutting tool path especially for large-scale material removal.

The contour parallel tool paths consist of contours of two types of offsetting. The very first offset of the boundary should be equal to the radius of the tool and then the usual offset based on the step over value is determined.

The contour parallel in-out strategy i.e. to cut the material from the middle of the pocket to the outside boundary is usually preferred as it involves first slotting with a minimum length of cut. Contrary to spiral-out tool paths, spiral in tool paths don't require boundary conformation as the first pass itself is the usual offset of the pocket boundary by the tool radius. These tool paths are usually practiced in automobile and aerospace industry where the thin walled boundaries have high rigidity requirements.

2.2. Tool path generation

The generation of a contour parallel tool path in a pocketing operation requires an offsetting operation of the inner boundary of the pocket and outer boundary of the island. The offsetting of a boundary has been a classical problem in computer graphics and consequently many methods from computer graphics are applied for contour parallel tool path generation.

The contour-parallel tool path generation can be divided into three different approaches: (1) 'pair-wise intersection', (2) 'Voronoi diagram', and (3) 'pixel-based'.

Offsetting of a boundary using 'pair-wise intersection' is a two stage process: (i) Determining the offset of the spline in an iterative manner until the error in the offset is reduced below a user defined limit (ii) detecting the singularities and redundant portions and correcting them.

Voronoi diagram is one the earliest approach to construct the contour parallel tool path. Held [5] utilized the method for creating the tool path, but restricted his approach for linear and circular segments, because these representations can easily be fed to CNC machines. Although this approach has been extended for non-linear segments, the method based on Voronoi diagram employs costly two dimensional boolean set operations, relatively expensive distance calculations and an overhead of extraneous geometry.

Similar to bypassing the step to detect and remove the self intersection features, a pixel simulation based approach for the offsetting is developed, where the tool path is generated by successive sweeping of the tool. This method is based on the Z-map and hence, high computational time and huge memory is required to achieve a desired level of precision due to its dependence on the resolution of the Z-map.

However, the adaptation of any method requires some preprocessing as well as post processing of the original method to make the generation of path efficient.

3. ENGAGEMENT ZONE MODELING

Cutter engagement is a measure that describes what portion of the cutter is actually involved in machining at a given instant of time. During complex milling operations, usually only a portion of cutter engages in cutting and, therefore the cutter engagement varies along the cutter path. The different engagement conditions for pocket milling are shown in
Fig. *2*. It is clear that as the tool is moving along the tool path the engagement condition can drastically change and hence the cutting loads.

Therefore, by monitoring the cutter engagement, we can monitor and control cutting forces. A sudden increase in cutter engagement may even result in tool breakage. Determination of cutter engagement is essential for adjusting feed rate. Cutter engagement value can also be used in generating efficient cutter paths [6].

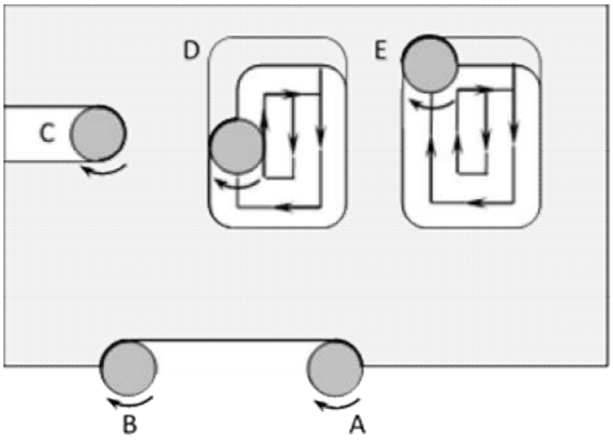


Fig. 2 Different Engagement Conditions, full engagement at scenario C and E, Half engagement for A, B and D[1]

A number of methods have been developed to calculate the engagement zone at any instant of 2.5D axis milling. These methods can be broadly divided into the following categories: (i) Analytical methods (ii) Discretized models (iii) Solid modeller based solutions. In Analytical modelling, the concept of half spaces is used to find the overall combinations of intersection of different part straight lines or circular arcs with the tool. The method yields results very fast, however, there are a number of limitations due to the analytical nature of the existing method [1]: limitation on work piece shape (only considers geometry with limited features like circles and straight lines, also there should be no cavity or hole in the initial geometry), limitations in work piece modelling (the equations of straight lines and circles must be provided), limitations in tool path (self intersecting tool path to be avoided).

Further, in discretized models, the primary focus is given on the material removal simulation of milling process by means of computer graphics. The primary goal of these simulations is to verify a given NC program for unwanted material removal and gouges in sculptured milling. The two main sub methods in this domain are: the vector method and the z-buffer technique. These methods have been used for the force calculation also in sculptured surface milling with consideration of tool deflection.

In solid modeling based methods, the standard Boolean operations are used to calculate the resultant geometry with the swept volume of the tool and the original work piece geometry. Although these Boolean operations are more computationally expensive than the other discretized methods, they represent the accurate geometry of engagement at each simulation step.

A solid modeling based extraction of CWE (Cutter Work piece Engagement) in feature based machining is carried out recently by Yip-Hoi and Huang [7].

Based on feature recognition, a database of different CWE corresponding to each feature is developed. However, there are two main assumptions that make it difficult to generalize the model for the actual 2.5D milling process. These assumptions are, first, the part should be rectangular prismatic and second the set up changes should be orthogonal to each other. Also, the approach depends upon the feature recognition capability of the system, which has its own limitations. Recently, Merdol et al. [8] has proposed a computational efficient algorithm for simulating the flute action on the arbitrary engagement zone either by CSG or Z-buffer and for reformulation of milling forces. The intersection points of flutes are computed analytically for simple engagement zones or numerically for complicated zones.

As the Constructive Solid Modeling represents the exact boundary information a general approach to extract CWE and further action of the helical flute is developed to calculate the cutting force. This approach doesn't require the feature extraction ability to be available in the system. It is an approach to simulate an arbitrary NC program with apparently no restriction on the initial work piece shape for 2.5 axes milling or higher.

Once the final part, raw work piece and the NC program are generated in any commercial software, the engagement areas can be calculated. The developed method, based on the solid modeling approach, inevitably calls for the Boolean operation between intersecting entities. Along the tool path, at any position of the tool, Boolean operations are required to update the work piece geometry and find the common entity (area) between the updated work piece and tool. In many cases it may happen that this engagement zone doesn't vary along some portion of the tool path. This portion is called force invariant feature and is already introduced in [7]. If the tool path segments are known, the number of Boolean operations can be significantly reduced.

4. MILLING MACHINING TIME EFFICIENCY MODELING

The machining time is one of the most important criteria to compare the machining efficiency of the tool path. The theoretical machining time is mostly obtained by summing up the time values from the division of each length segment with associated programmed feed rates.

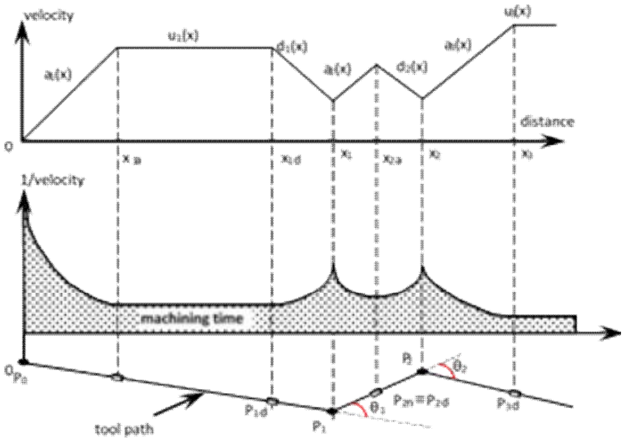


Fig. 3 Milling time modeling based on acceleration and deceleration of machine tool [9]

The theoretical machining time always underestimates the actual time because it does not take into account the effects of acceleration and deceleration of CNC machine. To compare the developed tool paths with the conventional ones, the machining time calculation based on the machining time model, which takes into account the controller's dynamic behaviour, has to be taken into account. Fig. 3 shows that the change in the direction of motion makes the feed rate profile vary due to the acceleration and deceleration of the machine tool.

Kim and Choi [9] concluded that the effect of acceleration and deceleration of a machine tool on the milling efficiency of various tool paths is large for high feed rate milling.

5. HSM TOOL PATHS

After the advent of High Speed Machining (HSM) in aerospace and automotive industries for machining complex machining parts made of aluminum and its alloys, the HSM is becoming increasingly popular as an innovative technology in all the manufacturing sectors. High Speed Milling assures two times more productivity, first in cutting speeds and second in feed rates. Modern High speed machine tools are capable of achieving very high spindle speed up to 50,000 RPM and traverse rates up to 16,000 mm/min.

In high speed milling (HSM), machining efficiency is improved by increasing cutting speed. For the purpose of lightening cutting resistance, reducing vibration and avoiding distortion, cutting depth is reduced in HSM, so that the operating load is lowered [10].

5.1. HSM considerations

The contour-parallel tool path generation is usually purely geometric in nature, which leads to a variation of radial depth of cut especially at sharp corners. The usual problems encountered due to this variation are: (i) left over material at corners (ii) sudden tool breakage, which leads to choosing worst scenario cutting conditions in manufacturing practices. Also, with the advent of high speed machining, the focus has been to develop smooth and curved tool paths for material removal to ensure machining quality.

From the machine dynamics and cutting tool point of view, the variation in the cutting load affects the tool life as well as the machine tool condition itself. Conventional contour parallel tool path based approaches such as spiral milling although they insure smooth tool paths; they result in a high variation of the radial depth of cut, which influences the tool load and machine dynamics.

Again as per the conventional paths, the problem specially arises at the corners and hence corner cutting or excess material removals at convex corners have long been studied analytically. For the general cases, there are two popular approaches mentioned in the literature to find the solution for the cutting load variation problem along the machining tool path: feed rate scheduling and tool path strategies. In feed rate scheduling, feed rates are typically programmed for the worst-case scenario to avoid tool breakage. Online optimization routines are sometimes used for maximizing material removal but that require a considerable amount of setup and maintenance efforts for the machine hardware.

The type of optimization depends upon the type of cutting tool used, its diameter, length, material, number of flutes and the work piece material. Further, these routines put an extra effort on the machine tool controller as well as the machine components to change feed rate for each block of NC code.

On the other hand, the approach to adapt or modify the tool path for achieving a constant load is independent from the cutting tool diameter, length, number of flutes and work piece material.

5.2. Corner cutting strategies

Further the generation of smooth tool paths could lead to high gains in machining time [11]. For the excess material removal at a sharp corner, circular loops are usually suggested. Zhao et al. [10] suggested the self-intersection like bi-arc transitions at each corner to avoid the restriction on the step over at a sharp corner in order to improve the tool path length **Error! Reference source not found.**. However, the tool is over engaged at the corners and needed to slow down at the corner. Also, the cutting direction is reversed as the tool travels from the apex of the loop to the end of the loop.

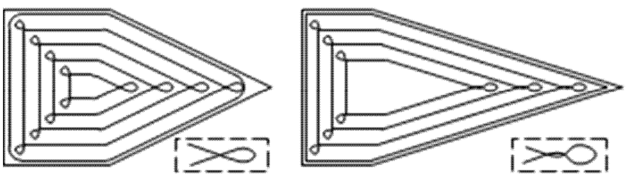


Fig. 4 The simulation of two type of biarc toolpath transitions. (a) Using the first type of biarc transition and (b) Using the second type of biarc transition [10]

A recent approach by Choy and Chan [4] describes the single loop and double loop strategy at the corner **Error! Reference source not found.**. However, their approach is limited to the nine combinations of clockwise circular, anticlockwise circular and straight line portion of the corners. Further, the number of loops required may be greater than two, which has not been addressed adequately.

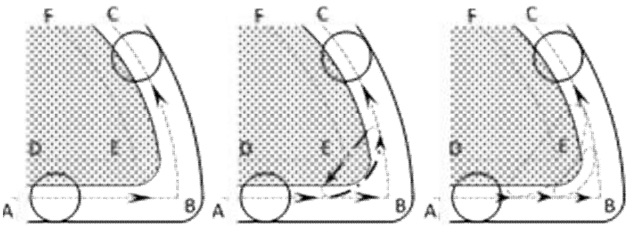


Fig. 5 Corner cutting strategies. (a) Conventional; (b) SLS; and (c) DLS.[4]

Further, Pateloup et al. [11] studied the behavior of different possible configurations of tool paths for a simple rectangular pocket geometry with right angle corners considering the dynamics of machining. The emphasis is given to maintain a minimum variation on the radial depth of cut on smooth tool paths. However, no automatic computing system is either specified or developed to generate the tool paths for complex geometries.

5.3. Generic tool paths

Dhanik [3] develop a recursive method to identify the excess material at the corners and to remove this material at each corner which is independent of segment types forming a corner and is generic in nature.

This method based on the signed distance function generate contour parallel tool paths which keep track of the in-process material boundary and confirms the material removal to the boundary of the pocket. Tool paths are smooth in nature for the high speed milling condition. This method and algorithms avoids the leftover material at the corners and minimizes the variation of radial depth of cut at each level of contour milling and consequently tries to maintain the same cutting conditions specified as the starting cutting parameters which are favorable for process reliability, part quality and tool life.

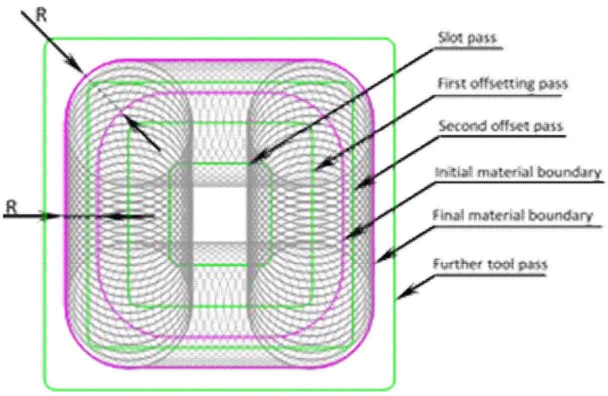


Fig. 6 The first offset pass and radial depth of cut variation [3]

In order to make a constant radial depth of cut, it is needed to modify the tool pass such that the material removal is same all along the tool path. Thus, for a given step over, the modified pass is determined by finding a boundary which is offset of the material boundary outwards by the amount of (Radius of tool- radial depth of cut). This concept is shown in Fig. 7. Note that the modified pass determined according to the above formulation coincide with the conventional tool path corresponding to the linear portion of the material line. But as soon as the material line deviates from the straight line the modified tool path also changes (the portion BC in Fig. 7 a). However, in this way the modified tool path also produces a new material line. This new material line is determined by offsetting outwards the modified tool pass by the value of tool radius. Proceeding in this manner may result in material left at the corners of the pockets. Thus an automatic program is conceptualized to detect and make additional passes to remove the material from these corner profiles.

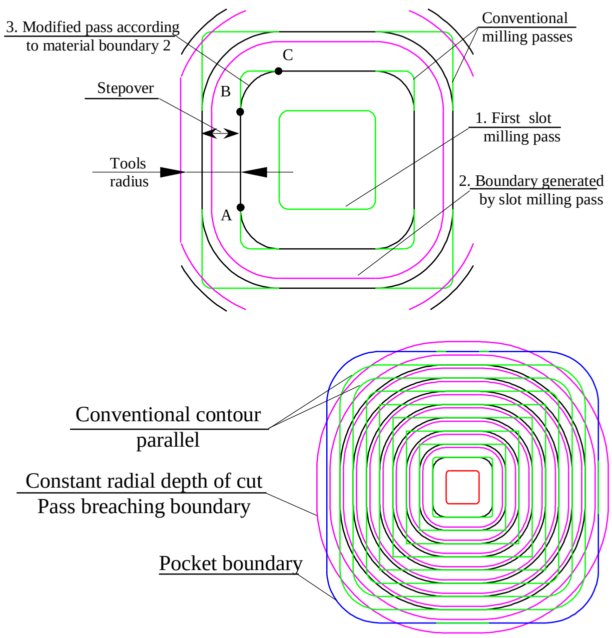


Fig. 7 Conception of Tool Path Modification [3]

The constant width of cut passes was achieved for spiral-out tool and the inevitable corner loops were constructed for the pocket to be constructed conforming to its required boundary.

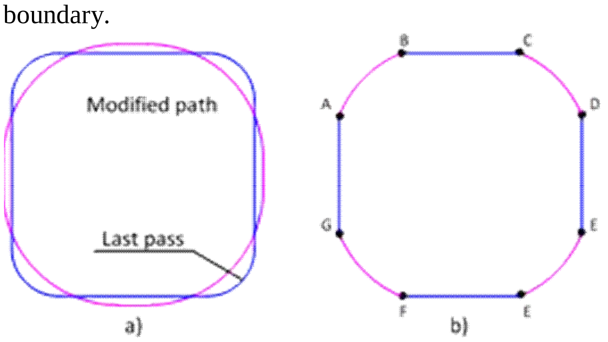


Fig. 8 Non-conformation of tool path (b) The conformed tool path [3]

5.4. Boundary conformed tool paths

Spiral in tool paths don't require boundary conformation as the first pass itself is the usual offset of the pocket boundary by the tool radius. These tool paths are practiced when the thin walled boundaries have high rigidity requirements. Thus, a slot milling pass at the boundary is utilized to minimize the change in the part rigidity. Dhanik [3] develop the method which optimize the successive contour parallel offsets for the smoothness as well as the engagement change. 'Efficient' geometrically feasible spiral in tool path which minimize the variation of the milling process engagement from its steady state while minimizing the curvature of the tool path is generated.

The geometry of the pocket for this method is assumed to be simple convex shaped which insures the inward offsetting always converges to a point or set of lines (called median axis) and there is no segregation of the offsets.

For a general non convex pocket segregation of offsetting area the problem of linking between different offsetting areas by tool retraction is observed and this has been found detrimental for the high speed machine tool efficiency.

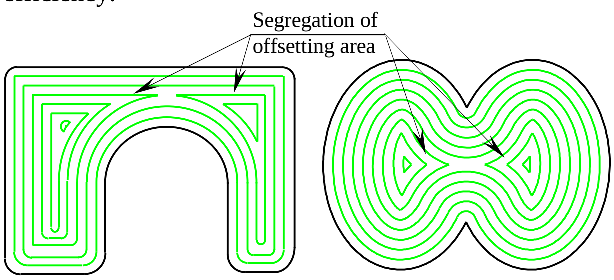


Fig. 9 Some examples of Segregation of offsetting area for non-convex geometries [3]

Hence, recent work has been focused on milling any arbitrary geometry of pocket without retraction of milling tool.

Held and Spielberger [12] developed smooth spiral tool paths for arbitrary pocket boundary composed of lines and circles where the radial depth of cut were kept strictly greater than zero and less than the maximum desired value. Different circles are fit along the median axis of the Voronoi diagram and their envelope is found and smoothened to develop the required tool pass. In general, Voronoi based HSM tool path offers an attractive solution to High speed milling requirements, yet this method is limited to pocket boundary with lines and circular arcs.

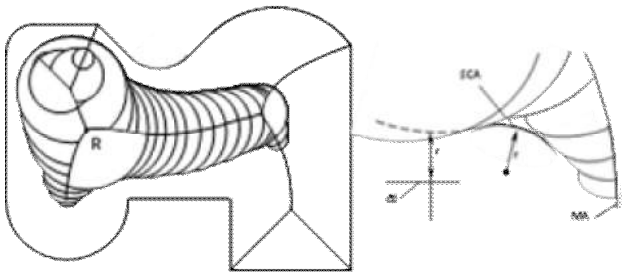


Fig. 10 Growing M-disks on the medial axis and smoothing circular arc [12]

In his work [3], Dhanik develop an alternative method to produce high speed milling compatible tool paths for arbitrary 2D pocket geometry with no tool retraction which are then optimized for the radial depth of cut or the engagement angle.

For a given closed boundary, signed distance function is used for initialization of the pocket boundary:

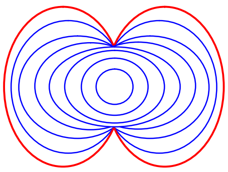
$$\emptyset(X,0) = \begin{cases} +d(X, X(0)), & X \in interior\ of\ X(0) \\ 0 & X \in X(0) \\ -d(X, X(0)), & X \in exterior\ of\ X(0) \end{cases} \quad (1)$$

Where, $d(X, X(0))$ represents the distance of point X from the pocket boundary $X(0)$. Then, curvature based motion low :

$$F_{curv} = -bk \quad (2)$$

is used for the tool path generation. According to this low the shrinkage speed of any closed boundary is proportional with its curvature at any point. Topology of the closed curve changes during the evolution and attains a circular profile of uniform curvature.

Next, the profiles in Figure 13, can be superimposed over each other and the smooth contours can be obtained for the tool path generation. It has been shown that the evolution of a curve is breaching the boundaries of the initial boundary. This can be observed for all non convex corners where the curvature is smaller than zero. This can be rectified by modifying the speed law:



$$F_{curv} = -bk \quad k \geq 0$$
$$F_{curv} = 0 \quad k < 0 \quad (3)$$

Fig. 11 The zero level curve at different time instants under the modified speed law [3]

The above formulation guarantees the boundary conforming contours converging to a circle and finally disappearing to a point. However, the radial depth of cut of the tool doesn't remain the same. While the minimum cutting width is visibly zero, the maximum cutting width depends upon the curve evolution time and instantaneous speed. Dhanik developed a method to constraint the motion of the curve in order to respect the maximum width of cut.

Method for generating boundary conformed pocketing tool paths is proposed by Chuang and Yang [13]. Based on the 2D Laplace parameterization of pocket contours and the redistribution of the original Laplace isoparametrics, continuous tool paths are generated. These generated tool paths have neither thin walls nor leftover tool marks. Detailed algorithms are formulated in following steps:

Step 1: Construct the final tool path for the pocket contouring.

Step 2: Divide the clearance border into four segments for applying Laplace parameterization.

Step 3: Generate 2D parameterization for the region enclosed by the clearance border.

Step 4: Reparametrize the 2D grids via arc-length based parametric redistribution.

Step 5: Construct final continuous tool path for pocketing.

The entire pocket machining can be achieved by a single spiral tool path. The complicated issue of path sequence selection is omitted. No intermediate tool retraction is needed. Meanwhile, the possibility of the existence of thin walls is automatically eliminated. Besides, the resultant single tool path is conformed to the profile of the pocket boundary. The method can be applied to general pockets either with or without islands.

Bieterman and Sandstrom[2] developed a method for curvilinear tool path generation for a pocket by spiraling between contours of a well-chosen scalar mathematical function on the pocket. By spiraling in this manner, the path is morphed from a very smooth shape in the pocket center to the shape of the part on the pocket boundary.

Unlike the conventional path, the spiral curvilinear tool path has low, nearly constant curvature near the pocket center and slowly changes into the part shape as it gets closer to the part boundary.

The mathematical function used to morph the curvilinear path is the approximate solution of a scalar elliptic second order partial differential equation "PDE" boundary value problem that appears in many engineering design analyses.

The PDE problem is defined on a two-dimensional pocket region whose boundary is offset inward, by one tool radius, from the part. Eigen value problem is solved approximately for the Laplacian:

$$-\nabla^2 u = \lambda u \quad (4)$$

subject to Dirichlet boundary conditions $u=0$ and the normalization:

$$max_{(x,y)} u(x,y) = 1 \quad (5)$$

for the principal Eigenfunction u (corresponding to the smallest of the positive eigenvalues $\left(\{\lambda_j\}_j = 1,\infty\right)$.

PDE like Eq. (4) is used because this kind of equation has properties that can be exploited to generate nearly optimal curvilinear spiral paths.

The spiraling that takes place is between appropriately spaced contours of u and continues, orbit by orbit, until all material is removed. The spacing is determined by a user-specified maximum step over, or width of cut.

The discrete tool path can be replaced with a twice continuously differentiable parametric spline curve that is fit to the discrete path. The variable feed rate was chosen tominimize machining time subject to limits on maximum componentaxis-drive velocity and acceleration and deceleration.

In the tool-wear experiments,a variable feedrate was set to keep material removal rate approximately constant.

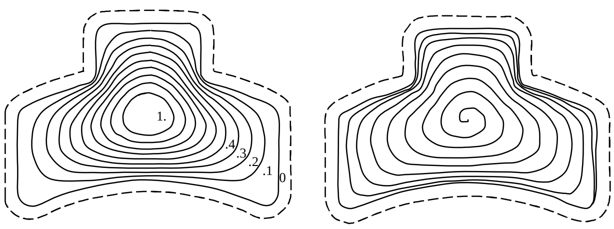


Fig. 12 a) Contours used to guide curvilinear tool path b) curvilinear tool path for pocket [2]

The morphing eliminates internal tight-radius corners in conventional paths and leads to major benefits such as machining time reduction, reduction of tool wear in cutting hard metals, reduced machine spindle wear and tear.

6. TOOL PATHS IN CAM SYSTEMS

In today's competitive environment, the milling process planner faces many challenges such as frequent changes in part design, demand on quality and high productivity. In order to meet these demands, a typical modern shop floor adopts advanced CAD/CAM (Computer Aided Design/Manufacturing) software and generic or application based High Speed CNC (Computer Numeric Control) machining centers. Today's CAD/CAM software are very successful for the construction of the tool paths to attain a desired shape on workpiece. Further, the compression of NC milling program data and dynamic feed
rate optimization are some advanced functionalities in modern CAD/CAM software[3].
Some softvers have High Feed Machining function which can optimize any 2-axis or 3-axis toolpath based on volume of material being removed and machine tool limitations to give efficient, varied feed rates tailored to each job. They can:

- Automatically vary feed rates based on volume: If there is more material to remove the cutter moves slower;If there is less material the cutter moves faster.
- Automatically ease the tool into and out of corners.

Fig. 13Advanced CAM Functionalities

Ideally, the whole area that needs to be cut to is milled with one continuous spiral tool path. Generally this is not possible. The iMachining Rough Cut algorithm developed in some softvers does the next best thing. It subdivides the area into the optimal number of sub-areas, each of which can be cut with a morphing spiral path, such that the total machining time for the whole area is minimal. It uses Modified D Type Tool Paths to cut slots to subdivide the area.
Another unique major advantage of the iMachining Rough Cut algorithm, is the fact that, on each point along the tool paths created, the values of the chip thickness, the feed and the spindle speed are always matched up according to the optimal rules laid down by the Technology Wizard.
The Morphing Spiral Tool Path is so called because unlike the spiral tool paths in most CAM systems, it gradually adapts to the shape of the area it has to clear, rather than symmetrically expanding in a circular fashion. This ability reduces machining time considerably.
Commercial CAM systems seldom consider the physical process concerns like transient thermal and mechanical loads generated during milling, which effect the part quality adversely and hence require trial experiments for new part design, and tool-workpiece combination.
Commercial CAM system are not able to compare various tool path strategies based on the various process related indicators. Tool path length is conventionally used as an indicator for process efficiency; however, in the context of High Speed Milling, it's a false indicator of milling process efficiency.
The HSM capabilities are not fully realized due to in process changes in cutting conditions with instantaneous in-process workpiece geometry varying along the tool path.

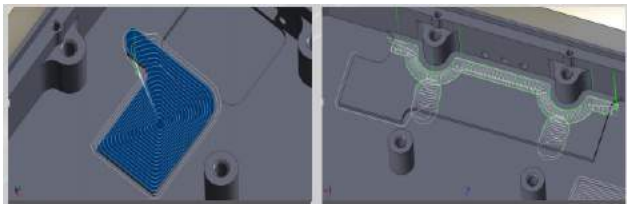


Fig. 14 Morphing Spirals and Intelligent Separation in a iMachining

7. CONCLUSION

Tool paths modifiedfor HSM application must have the following properties:
i. It should consider the effect of limiting process considerations like force, vibration and chatter for stable milling of the tool path.
ii. The physical process parameters like cutting forces, temperature etc. shouldremain constant or maintain a minimum fluctuation around a preset specifiedaverage value.
iii. The tool path must be c^1 continuous for avoiding detrimental effect of chipthinning therefore the sudden fluctuation of the feed rate should be avoided.
iv. The tool path should adhere to a c^2 continuity, however this condition may beviolated easily as the tool path processing for a typical machine tool consists oflines and arcs. The notion of spline is relatively new and not a well establishedstandard in practical milling [3].
With respect to point i, ii, and iii, one possibility to avoid sharp corner is to post-processthe conventional tool path by fitting arcs, loops or other curves for successive machining of the corner [4],[11],[10]. This leads to smaller cutting forces and less feedrate fluctuationswhile milling corner.
Another possibility is to develop a smooth spiral tool path generation using the solutionof an elliptical partial differential equation boundary value problem. Laplace basedparameterization and meshing of the domain to be machined produces smoother contourparallel tool paths [2],[13] than the conventional contour parallel tool paths, thus makesthis method suitable for the tool path generation for the roughing process.

In summary, the following are the drawbacks of existing tool path generation methods:

• Adaptation of conventional tool paths for HSM purpose requires some arc orcurve fitting for the original tool path partially or entirely, this curvefitting may require extra efforts and preprocessing of existing tool path and hencesusceptible to errors.

• Smooth tool paths constructed, for the low curvature changes along the tool path,by mapping of tool path from a parameterized space to the pocket area are proneto changes in the engagement conditions in an uncontrolled way along the toolpaths.

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