

Tool Path Planning Using Trochoid Cycles for Hardened Steel in Die and Mold Manufacturing (1st Report)

— Tool Path Generation for Trochoid Cycles Based on Voronoi Diagram —

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ABSTRACT: Rough cutting of hardened steel by a straight end mill has been recognized as a key strategy to enhance the productivity in die and mold manufacturing. The conventional tool planning strategy based on contour parallel paths often causes an excessive tool load at specific regions such as a sharp corner. We propose a tool path generation strategy with trochoid cycles to remove such a critical cutting region. Trochoidal tool paths can be generated for an arbitrary two-dimensional pocket contour by using the proposed algorithm based on the Voronoi diagram. Preliminary machining tests are presented to show the effectiveness of the trochoidal grooving to avoid an excessive tool load.

Key Words: die and mold manufacturing, tool path planning, end mill, contour parallel paths, trochoid cycles, Voronoi diagram

1 INTRODUCTION

Conventionally, dies and molds of the hardness HRC53 or above are typically machined by the process illustrated in Figure 1(a) [1]. Raw die steel, such as JIS SKD61 typically of the hardness HRC28, is machined through rough and finish cutting, and then is hardened by heat treatment before rough and finish grinding or EDM (electric discharging machining). It requires many different machining processes and many machine tools, which results in high percentage of the total process lead time being wasted for non-processing operations such as loading and unloading.

In early '90s, a sintered carbide end mill with an (Al, Ti)N coating was introduced into the market, which made it possible to directly machine pre-hardened steel of the hardness up to HRC53. By first performing heat treatment on raw steel and then machining it by using this tool, die/mold making process can be integrated as shown in Figure 1(b). It not only reduces the total process lead time, but also possibly eliminates the need for a polishing process conventionally done by a human expert.

However, even with this tool, the machining of hardened steel requires a very careful process planning. The hardness ratio of (Al, Ti)N coating and pre-hardened SKD61 is typically 2.3~4.6 [1], which may not be sufficiently high for safe machining. Dies and molds generally have a complex three-

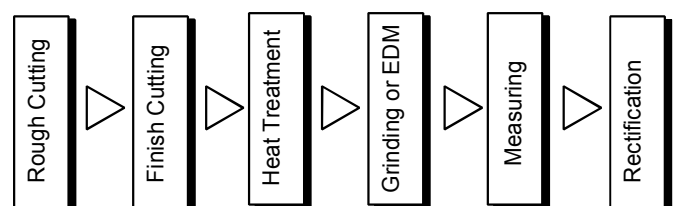


Figure 1. (a) Conventional die and mold manufacturing procedure

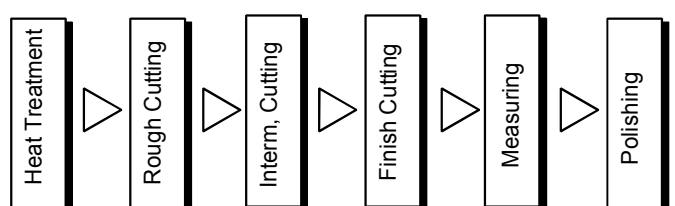


Figure 1. (b) Die and mold machining on hardened steel

dimensional geometry. To generate tool paths, commercial CAM software mostly employ either contour-parallel or direction-parallel machining strategies. In practice, however, it is very difficult to use the CAM output without any modification by a human operator. For example, contour-parallel paths are often subject to an abrupt change in the tool engagement particularly on sharp corners [2]. In the machining of hard materials, such an abrupt increase in the tool engagement easily causes an abrupt increase in the cutting force, which may result in an abnormal tool damage such as the chipping or the breakage. It is also clear that the variation in cutting forces causes the deflection of an end mill, which manifests as dimensional and surface-finish errors on the machined part [3]. To avoid it, a process planner must very carefully choose cutting conditions or manually modify the paths. For example, if the feedrate is too high or the radial depth of cut is too large on such a high tool load region, it easily causes severe tool damage. If machining conditions are too conservative, it sacrifices the machining productivity.

This paper proposes a tool path planning scheme for high-speed machining of dies and molds. On contour-parallel paths, circle milling paths (referred to as *trochoid cycles* in this paper) are inserted to remove particular regions that are subject to higher cutting load. The insertion of trochoid cycles allows much safer machining without careful design of cutting conditions. It is of particular interest in the machining of hard materials by a straight end mill.

In this first report, we will mainly present an algorithm to generate trochoid paths. In our second report [4], we will present a comprehensive tool path planning strategy using trochoid cycles. In particular, we will discuss how to find high tool load regions on contour parallel paths, and where to insert trochoid cycles. Practical case studies will be also presented in the second report.

The remainder of this paper is organized as follows. The next section reviews issues related to contour-parallel paths. Section 3 presents an algorithm to generate trochoidal tool paths to cut an arbitrary contour. A preliminary machining test is presented in Section 4. Section 5 discusses the conclusions drawn from this paper.

2 ISSUES IN TWO DIMENSIONAL TOOL PATH PLANNING

2.1 Issues in two dimensional tool path planning

Two approaches to tool path planning have dominated the research literature and commercial implementation of algorithms for 2-1/2 dimensional tool path generation. Contour-parallel and direction-parallel machining strategies are both geometrically appealing and computationally tractable. Numerous

researches have been conducted to develop numerically efficient algorithms for robust tool path generation that can handle arbitrarily shaped pockets with multiple islands [5]. In today's market, many commercial CAM software are available with such an algorithm implemented.

Contour-parallel paths are geometrically computed to remove the required material with little attention paid to issues of machining technology. As a result, particularly in high-speed machining of hardened steel, it often causes a problem. Figure 2 illustrates the increase of cutting forces on a corner cutting as an example. It is clear that the tool engagement angle abruptly increases at a sharp corner, which results in an abrupt increase in the cutting load. Particularly in high-speed machining, it easily causes severe tool damage such as the chipping.

It is also a critical issue that the innermost contour-parallel path in pocketing must be often cut by a full immersion slotting. Slot cutting generally results in a very high tool load.

2.2 A review on machining strategies to avoid an excessive tool load

In order to avoid the tool damage, a process planner must careful choose various cutting conditions, such as the feedrate, the radial depth of cut, and the axial depth of cut. For example, if the tool is slowed down at a corner, an abrupt increase in cutting forces can be suppressed.

Numerous researchers have been studying cutting force control approaches by the feedrate regulation since the 70's. Cutting force control approaches can be classified roughly into three: 1) feedback control approaches, where the cutting force is somehow monitored on-line and the feedrate is regulated accordingly by typically using an adaptive control scheme (e.g. [6]), 2) model-based feedforward control approaches, where a process simulator predicts the cutting force along the given CL data and optimizes the feedrate in priori (e.g. [7]), and 3) their combinations (e.g. [8]). Some latest commercial CAM software adopt a simple feedrate optimization scheme (e.g. *TOOLS* by Graphic Products, Inc. [9]).

Although such a feedrate regulation approach is effective to some extent to optimize the productivity

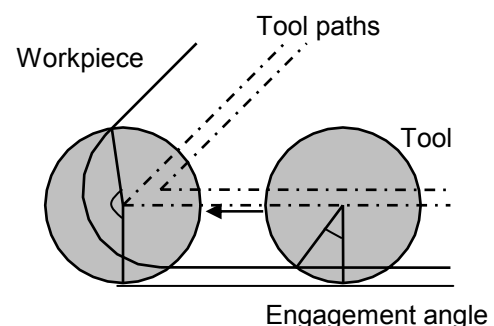


Figure 2. Schematics of corner cutting

with avoiding an excessive tool load, there are issues to be addressed. For example, it is often the case that the feedrate must be slowed too much at sharp corners, which may significantly sacrifice the overall productivity. Furthermore, experimental studies showed that the regulation of cutting forces to a constant level on a curved path does not always extend the tool life to the level on a straight path [10]. Adachi [11] experimentally verified that it was mostly due to the cutting heat that increases when the feedrate is reduced at a corner.

To avoid higher cutting temperature on a corner, the tool path itself must be modified. There have been relatively little works done to modify tool paths in this context. Iwabe et al. [12] proposed to insert an additional circular-arc loop at a convex corner to keep cutter engagement below the prescribed limit. This strategy is indeed adopted in some of the latest commercial CAM software such as *TOOLS* or *Master CAM* by CNC Software, Inc. [13]. A notably unique approach was proposed by Stori and Wright [14], where an offset path is modified such that the instantaneous engagement angle of the cutting tool is always maintained at a desired constant level. The algorithm can be, however, applied only to convex contours, which is too strong a restriction for practical implementation.

2.3 Tool path planning using trochoid cycles to remove high tool load areas

As can be seen in the example shown in Figure 3, the regions that are potentially subject to a higher cutting load (referred to as the critical cutting region hereafter) typically lie on the innermost loop, where a full immersion slotting is required, and on sharp corners, where the cutting engagement angle abruptly increases. We propose to use trochoidal grooving to remove such a region before moving to contour parallel paths. In this paper, we call circle milling paths shown in Figure 4 trochoid cycles.

3 TOOL PATH GENERATION FOR TROCHOID CYCLES

If the center trajectory of trochoid cycles is given, and the radius of each circle is constant as shown in

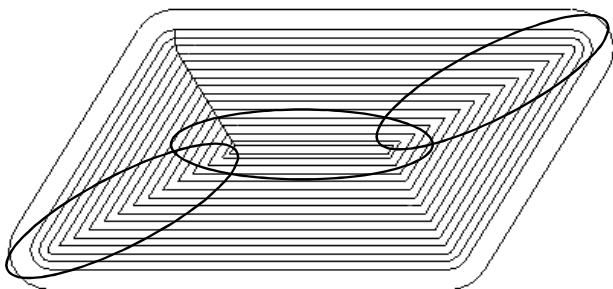


Figure 3. An example of potential critical cutting regions

Figure 4, then the tool path (tool center trajectory) generation of trochoid cycles is trivial. This chapter considers the case where the contour to be cut by trochoid cycles is given arbitrarily.

3.1 Voronoi diagram

3.1.1 Definition of Voronoi diagram

Persson [15] proposed in 1978 an algorithm to generate a contour-parallel path for an arbitrary shaped pocket by using the Voronoi diagram. The Voronoi diagram also plays a crucial role in the algorithm proposed in this paper to generate trochoidal tool paths. The Voronoi diagram is defined as follows [16, 17]. Consider a set, S , of disjoint points and straight-line segments in the two dimensional Euclidean space E^2 . The points and line segments contained in S are called *sites*. In our application, this set defines the contour to be machined by trochoid cycles.

Definition 1: For a point, $p \in E^2$, and a site s , the (Euclidean) distance from p to s is the minimum of the distance between p and q , $d(p,q)$, for q out of the closure of s .

Definition 2 (clearance disk): The clearance $d(p,S)$ of p with respect to S is defined as the minimum distance from p to any site $s \in S$. The clearance disk at p is the disk with radius $d(p,S)$ centered at p .

Obviously, every clearance disk touches at least one site of S . For given S , the Voronoi diagram is defined as follows:

Definition 3 (Voronoi diagram): The Voronoi diagram $VD(S)$ is the set of points in E^2 whose clearance disks touch at least two disjoint sites in S .

In other words, the Voronoi diagram $VD(S)$ is defined as a set of points which have at least two sites in S in the same distance, and all the other sites in S are further than them. The points and segments that form the Voronoi diagram are called *edges*.

Definition 4 (Medial axis): For $VD(S)$ of a closed contour S , a set of edges excluding those connected to a reflex vertex of S is called the medial axis of S , $MA(S)$.

Figure 5(a) and (b) respectively shows an example of the Voronoi diagram and the medial axis.

3.1.2 Computation of Voronoi diagram

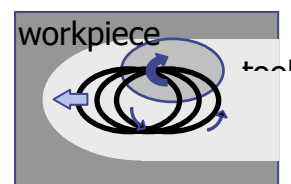


Figure 4. Trochoid cycles

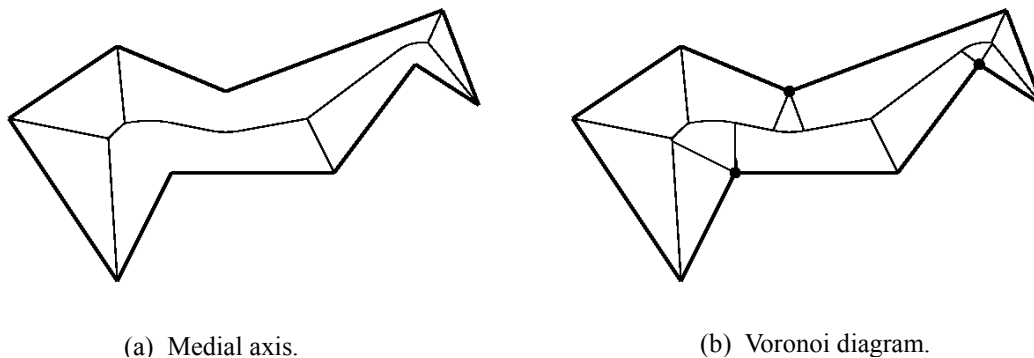


Figure 5. Examples of the medial axis and the Voronoi diagram [17]

It is not easy to develop an efficient, and numerically stable algorithm to compute the Voronoi diagram, particularly when S contains not only points but also line segments. There are, however, several algorithms available, and some of them are implemented in popular platforms such as ANSI C or Fortran, and open to the public. In this paper, we use *vroni*, ANSI C codes developed by Held [18]. Its detailed algorithm is presented in [16].

We note that there have been active research efforts to develop a further efficient algorithm to compute a Voronoi diagram (e.g. Choi and Inui [19]).

3.2 Generating a trochoidal tool path based on the Voronoi diagram

Suppose that a set of disjoint points and straight-line segments that defines the contour is given. This section presents an algorithm to compute a trajectory of tool center to cut this contour only by trochoid cycles. First, define the set, S , by offsetting the contour to the inside by the radius of the tool, r . Suppose that the medial axis for S is given. Notice that it is always possible to draw an inscribed circle centered at any point on the medial axis. In other words, if the pitch between each clearance disk is sufficiently small, then a set of all clearance disks covers the entire contour S . Therefore, by combining such clearance disks with the prescribed pitch, trochoid cycles to cut the entire contour can be easily obtained. Notice that a segment that is on the Voronoi edges, $VD(S)$, but not in the medial axis, $MA(S)$, must not be a part of the “centerline”, since the inscribed circle centered on such a segment touches S by one point. Such a circle does not contribute to machine the pocket contour.

The algorithm to generate trochoid cycles can be summarized as follows:

- 1) Compute the medial axis for S , $MA(S)$.
- 2) Choose the edges that form the “centerline” from $MA(S)$ (denote it by $CL(S)$). When the starting and end points are given, they can be trivially found.
- 3) Let a point p be the starting point, which belongs to the edge, $e_i \in CL(S)$ ($i=1$).
- 4) Find two segments in the contour, $s_1, s_2 \in S$, that are

the closest to e_i . Draw a clearance disk centered at p that touches s_1 and s_2 . Crop the arc between two points of contact in the heading direction.

- 5) Add an air cut part as shown in Figure 6. To minimize an air cut, the points B and C are connected by a straight line instead of an arc.
- 6) Move p to the heading direction by the prescribed pitch along the edge e_i . The pitch must be given such that the maximum radial depth of cut is kept constant.
- 7) Repeat 4)~6) until the end of the edge, e_i , is reached. When it is reached, move to the next edge, e_{i+1} .
- 8) Repeat 4)~7) until the end point is reached.

Figure 7 shows an example of trochoid cycles. For the simplicity of the computation, a straight air cut path was not used. For the clarity of the figure, trochoid cycles were computed only along one branch of the medial axis. Trochoid cycles can be easily extended to fill four corners.

4 A PRELIMINARY MACHINING TEST

4.1 Objectives and Experimental Setup

This chapter presents a preliminary machining test to demonstrate the use of trochoid cycles in pocketing. The objective of machining tests is to show that (a) when a contour parallel path is used, a severe tool load cannot be avoided particularly in slotting the innermost path, and (b) it can be avoided by inserting trochoid cycles.

Figure 8 shows the geometry of the pocket. The depth of the pocket is 6.0 mm. The workpiece material is carbon steel, S50C.

A medium-sized vertical-type machining center, VM4-II by OKK Corp., was used throughout machining tests. Cutting forces in the X- and Y-directions are measured by using a dynamometer (Kistler Instrument Corp.'s 9272 piezoelectric four-component dynamometer). A solid straight end mill with (Al, Ti, S)N coating is used. Its specifications are shown in Table 1.

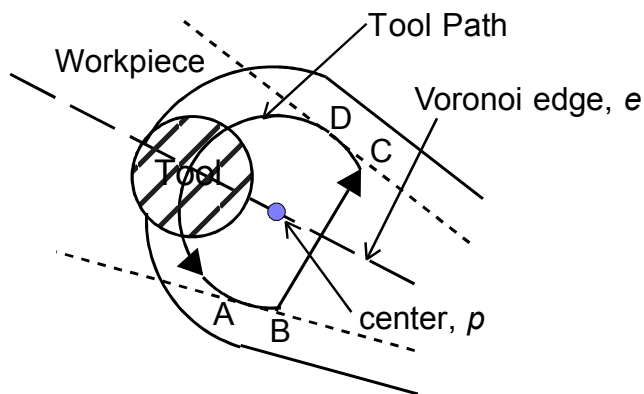


Figure 6. One trochoid cycle

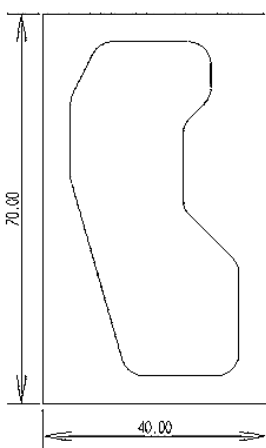


Figure 8 Geometry of the pocket

Table 1 Major specifications of the tool

Type	straight end mill
Material and coating	Sintered Carbide with (Al, Ti, S)N coating
Cutter diameter	6 mm
Number of flutes	4

4.2 Tool paths and cutting conditions

Figure 9(a) illustrates contour parallel tool paths (denoted by “Strategy (a)”). Notice that the innermost path must be cut by a full immersion slotting. Since we found in pre-machining tests that it was difficult to slot cut this region without an excessive tool load, this region is repeatedly machined with the axial depth of cut of 2mm, 1/3 of the pocket depth, at each layer. Such a manual modification of tool paths or machining conditions is commonly needed when a contour parallel path is used also in real-world die and mold manufacturing.

Figure 9(b) illustrates the proposed tool path planning with trochoidal grooving (denoted by “Strategy (b)”). The geometry that is machined by trochoidal grooving is determined such that the diameter of a trochoid cycle is at least 1.5 times as large as the tool

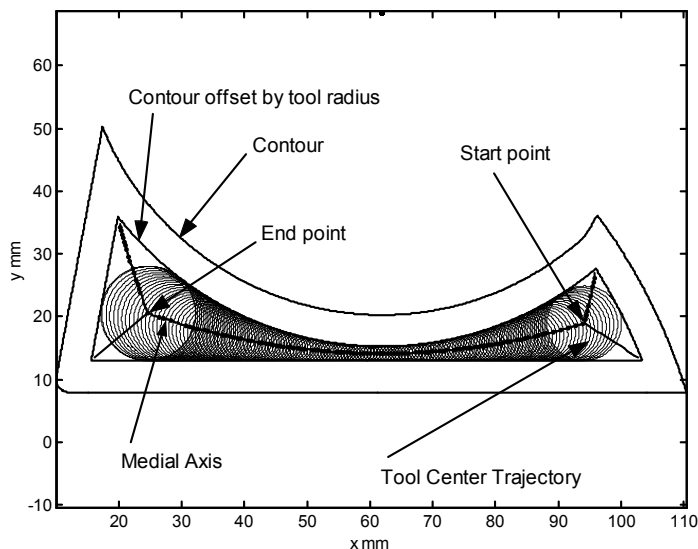


Figure 7. An example of trochoid cycles

diameter. A circular cutting with too small diameter is likely to cause severe tool damage just as slotting (see our second report [4]). The rest of the pocket is machined by contour parallel paths.

Table 2 summarizes cutting conditions. These conditions are determined based on pre-machining tests. The entire machining is dry cut under an air blow.

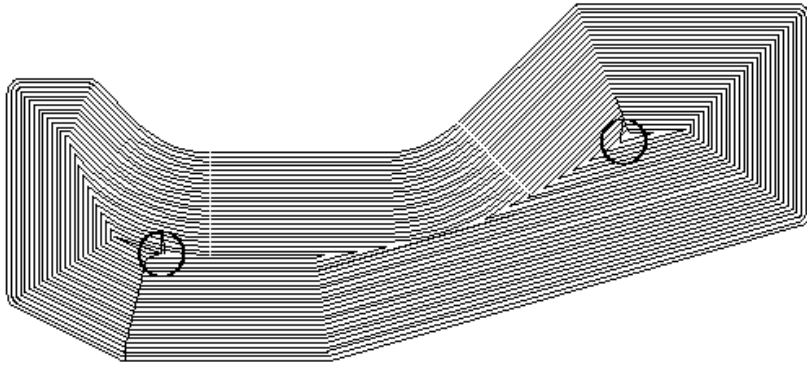
4.3 Machining results

Figure 10 compares the cutting force on the XY plane measured over the entire path in the strategies (a) and (b), respectively. Note that the cutting force in the Z-direction is not measured, which is why the cutting force on helical boring seems low.

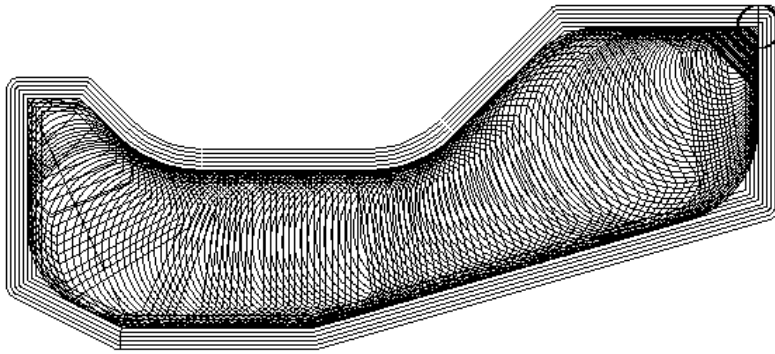
In Figure 10 (a), the tool is subject to the maximum cutting load of about 700 N, which is quite severe for a $\phi 6$ tool. The maximum cutting force is observed right after the helical boring, where the hole is expanded along the contour parallel path. As was discussed in Section 2, inner paths are subject to a higher cutting load since they are likely to have sharper corners. On the other hand, in Figure 10(b), the cutting load is at most 150 N, and its variation was much smaller than the previous case. The employment of trochoid cycles made the whole machining process much safer.

Figure 11(a-1)~(b-2) show the tool wear observed by a CCD camera when the machining is finished. It can be observed that Strategy (a) resulted in a significantly large tool wear on the tool tip, while Strategy (b) caused a slightly larger tool wear on the edge. It implies that Strategy (a) caused a larger variation in the tool deflection, which is due to the variation in the cutting load. We also note that the surface finish on the pocket bottom was better when Strategy (b) was used.

The total machining time was 348 seconds with Strategy (a), while it was 573 seconds with Strategy (b). Note that both strategies share exactly the same contour parallel paths on the outer part. When these



(a) Strategy (a) — Contour parallel paths



(b) Strategy (b) — With trochoidal grooving

Figure 9 Conventional and proposed tool path planning

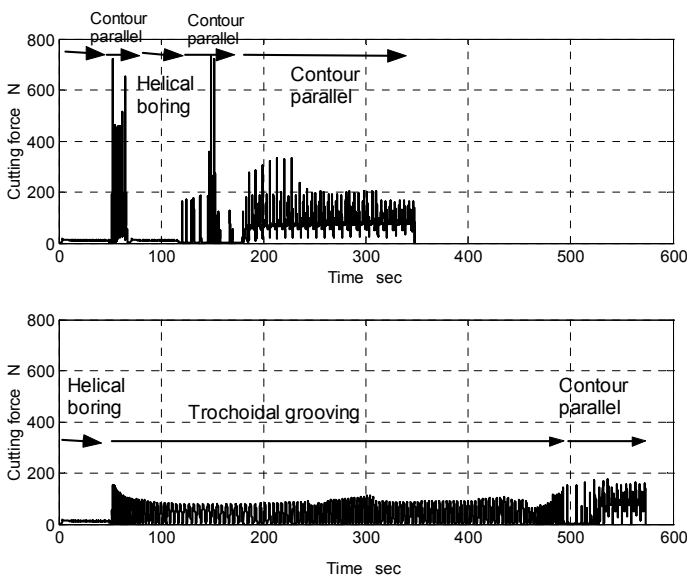
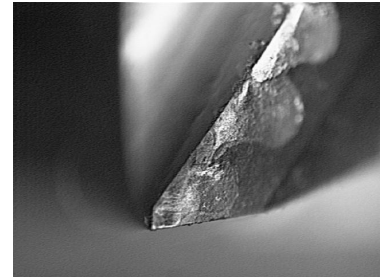


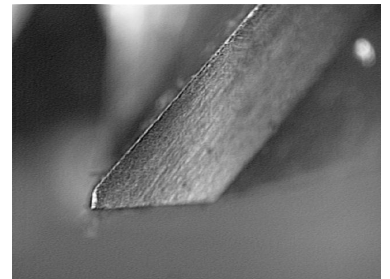
Fig.10. Comparison of cutting forces on the X-Y plane with Strategy (a) (above) and Strategy (b) (below)

paths are excluded, the machining time was 210 seconds with Strategy (a), and 440 seconds with Strategy (b). Since every trochoid cycle contains an air cut, it inevitably consumes more non-cutting time. In the machining test, however, the trochoid cycles were subject to the cutting load of about 70~80 N in Figure 10 (below), which was much lower than that in the corresponding part in Figure 10 (above). It implies that we can possibly increase the feedrate and/or the trochoidal pitch, which will shorten the total lead time. Furthermore, in this machining test, the feedrate was constant over each trochoid cycle. Each trochoid cycle is subject to a

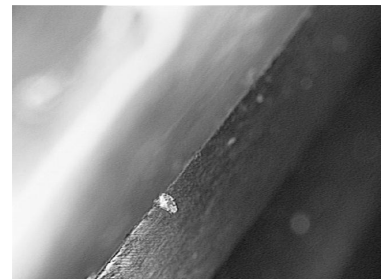
(a-1)
Tool tip — Strategy (a)



(b-1)
Tool tip — Strategy (b)



(a-2)
Flute edge — Strategy (a)



(b-2)
Flute edge — Strategy (b)



Figure 11. Comparison of tool wear observed by a CCD camera when the machining is finished

Table 2 Machining conditions

	Axial depth of cut (mm)	Radial depth of cut (mm)	Feedrate (mm/min)	Spindle speed (min ⁻¹)
Side cut	6.0	0.3	960	4800
Slotting	2.0	-	480	4800
Trochoidal grooving	6.0	0.4	480	4800
Helical boring	0.3	-	240	2400

smaller cutting load on the entry and the exit, and a higher load in the middle. The feedrate can be optimized by using a process model to predict the cutting force such that the cutting force is regulated constant over each trochoid cycle [11]. By applying this feedrate optimization, the machining time can be further shortened without increasing the maximum cutting force.

5 CONCLUSIONS

This paper presented a tool path planning strategy to avoid an excessive tool load in two dimensional pocketing. The proposed strategy employs trochoid cycles to groove critical cutting regions, such as the innermost region that must be slot cut in contour parallel machining, or sharp corners. In particular, this paper presented an algorithm to generate trochoid cycles to cut a two-dimensional pocket contour of the given arbitrary geometry based on the Voronoi diagram.

Preliminary machining tests were conducted to conclude the following:

- (1) In the conventional strategy, where contour parallel paths are mostly used to machine the entire pocket, the tool is likely subject to a higher cutting load particularly on the innermost region. For the machining of a harder material, a very careful design of cutting conditions is crucial to avoid critical tool damage, which requires profound knowledge and experiences of an expert process planner.
- (2) By using trochoid cycles, higher tool load regions can be safely machined. However, since every trochoid cycle contains an air cut, it likely takes more total machining lead time. It is favorable from the viewpoint of shortening the total machining time to minimize the area cut by trochoidal grooving.

This paper only presented how to construct trochoid cycles when the geometry of the contour to be cut is given. In our second report [4], we will present a more comprehensive tool path planning methodology to show how to find a high tool load region on contour parallel paths, and where to insert a trochoid cycle. Then, we will present more practical case studies of 2-1/2 dimensional machining of a cavity mold.

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