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Tool Path Planning Using Trochoid Cycles for Hardened Steel in Die and Mold Manufacturing (2^{nd} Report)

— Tool Path Planning to Avoid an Excessive Tool Load —

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ABSTRACT: In the machining of hardened steel for die and mold manufacturing, contour parallel paths often cause an excessive tool load in a critical cutting region such as the region where a full immersion slotting is needed, a sharp corner, or a narrow slot. The insertion of trochoid cycles is effective to safely machine such a region. Two practical case studies of 2-1/2 dimensional machining of a cavity mold are presented to show the effectiveness of the proposed machining strategy using a straight end mill for higher productivity machining, compared to the conventional machining strategy using a ball end mill.

Key Words: die and mold manufacturing, tool path planning, contour parallel path, trochoidal grooving, straight end mill, ball end mill

1 INTRODUCTION

High speed cutting of hardened steel, such as JIS SKD61 of the hardness up to HRC53, became possible by the introduction of a sintered carbide end mill coated by (Al, Ti)N in the 90's. However, even with this tool, a very careful process planning is crucial in the machining of hardened steel. Particularly in die and mold machining where a complex three-dimensional geometry is often machined, a contour-parallel path often causes a problem. For example, it is subject to an abrupt change in the tool engagement angle on a sharp corner. It naturally causes an abrupt change in cutting forces, which may result in abnormal tool damage such as the chipping or the breakage. To avoid it, a expert process planner must very carefully choose cutting conditions or manually modify tool paths.

In our first report [1], we presented an algorithm to generate trochoid paths to machine a two-dimensional contour of an arbitrary geometry. Trochoidal grooving can be used to safely remove the region that is subject to a higher cutting load on contour parallel paths. In this second report, we will present a comprehensive tool path planning scheme to show how to find such a high tool load area on contour parallel paths, and where to insert trochoid paths.

We will also present two case studies of 2-1/2 dimensional machining of a cavity mold, where the proposed machining strategy is applied to a high productivity machining of hardened steel with a straight end mill. By comparing with the conventional machining strategy with a ball end mill, we will show the effectiveness of the proposed strategy to enhance the overall productivity without sacrificing the tool life.

2 TOOL PATH PLANNING TO AVOID CRITICAL CUTTING REGIONS

2.1 *Finding critical cutting regions*

To illustrate the application of trochoidal grooving, we consider the pocketing of the contour shown in Figure 1 as an example. Contour-parallel paths for this pocket are also shown. It can be easily understood that the tool will be subject to a higher cutting load on the innermost path, since a large portion of this path must be machined by full immersion slotting. Furthermore, the tool will be subject to an abrupt change in cutting forces on sharp corners (see Figure 2 in [1]). In this paper, such a region is referred to as the critical cutting region.

A machining process simulation is conducted to compute the tool engagement angle all over the tool path shown in Figure 1. It can be computed based the geometrical interference of the tool and the pre-machined surface [2]. The tool diameter is assumed to be 10 mm in this example. Figure 2 highlights the

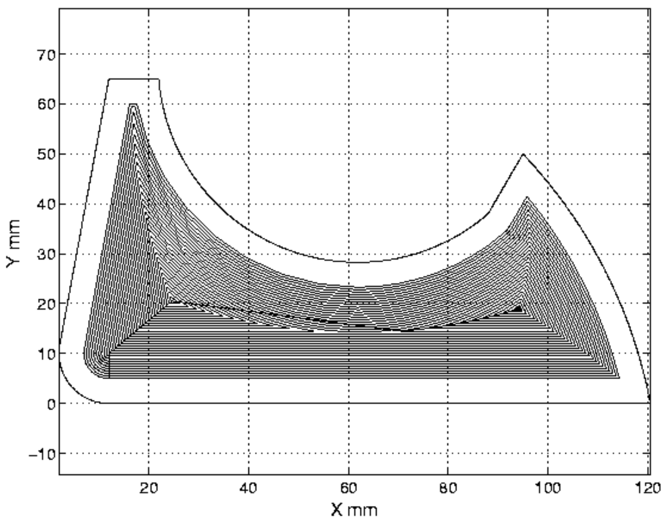


Figure 1. The pocket contour and contour parallel paths

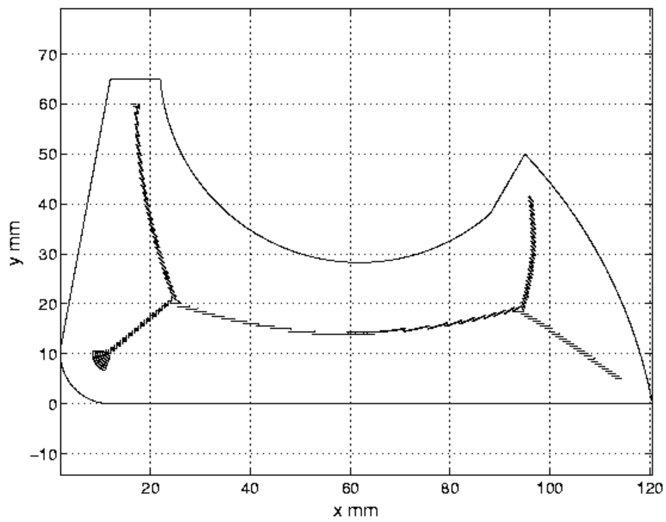


Figure 2. The critical cutting region with the engagement angle larger than 40 degrees

critical cutting region that is subject to the engagement angle larger than 40 deg.

Figure 3 shows the medial axis of the contour. See our first report [1] and the references therein about the medial axis. From Figure 2 and 3, it can be clearly seen that *the critical cutting region always lies on the medial axis*. Needless to say, not every portion of the medial axis constitute the critical cutting region. By computing the engagement angle only on contact points of the medial axis and tool paths, we can find the branch of the medial axis that belongs to the critical cutting region. It eliminates the need to perform a machining process simulation all over the tool path to compute the engagement angle.

2.2 Inserting trochoid cycles

By inserting trochoid cycles presented in our first report [1], such a critical cutting region can be safely machined. In Figure 4, trochoid cycles of the radius of 2 mm are inserted on contour parallel paths. The trochoidal radius was determined such that the ratio the diameter of the machined surface to the tool diameter to becomes 1.2 (see Section 2.3). In Figure 4, trochoid cycles are inserted only on three branches of the medial axis. As has been implied in [1], trochoidal grooving often extends the total machining lead time due to its air cut. In this example, trochoid cycles are inserted only on particularly sharper corners to minimize the area of trochoidal grooving,

By using the algorithm presented in [1], trochoid cycles of variable radius can be used to machine along a contour parallel path, as shown in Figure 5. It should be, however, noted that from the reason above, it may not necessarily reduce the total machining time.

2.3 Grooving a narrow slot

When a contour parallel path is used, a narrow slot is often cut by a full immersion slotting, which inevitably imposes a critical load on the tool. As discussed in the previous section, such a region can be safely machined by trochoidal grooving. However, when the slot is too narrow compared to the tool diameter, the trochoidal radius becomes too small. In such a

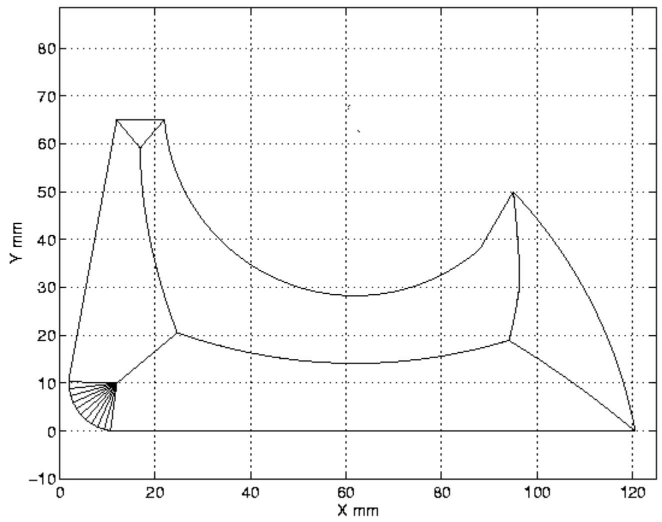


Figure 3. Medial Axis

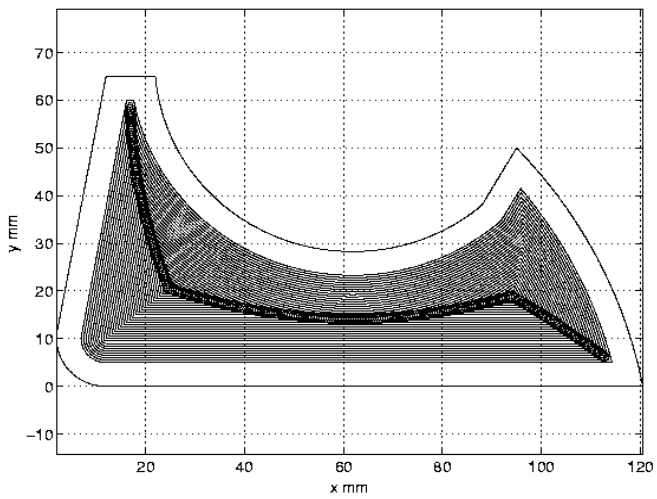


Figure 4. Trochoidal grooving inserted

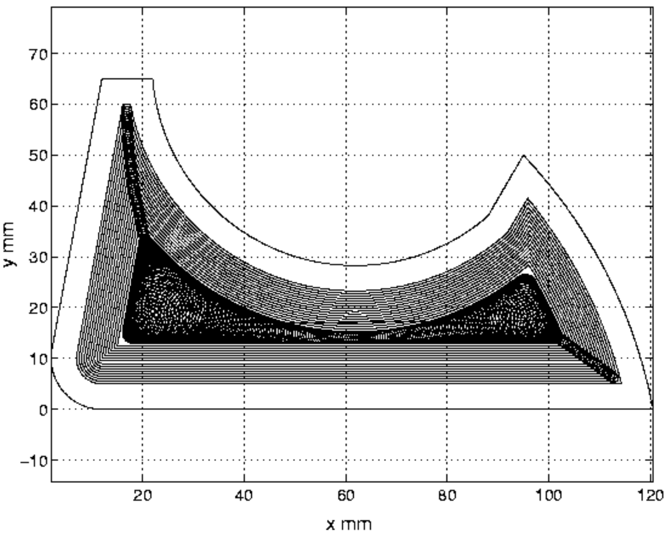


Figure 5. Trochoid cycles of variable radius inserted

case, trochoidal grooving becomes essentially the same as a full-immersion slotting. In real-world die and mold machining, such a narrow region can be often found.

The only way to safely machine such a region is to reduce the axial depth of cut, unless the tool can be exchanged to the one of a smaller diameter. That is, such a region, referred to as *the z-cut division region* hereafter, must be machined repeatedly with a smaller axial depth of cut (typically 2~3mm) by using trochoid cycles or a full immersion slotting.

Figure 6 illustrates machining strategies for grooving a narrow slot. In Region A, where the ratio of the radius of the machined surface, R, to the tool radius, r, is 2.0~3.0 or larger, original contour parallel paths can be used. In Region B, where R/r is smaller than 2.0~3.0 but larger than 1.1, trochoidal grooving should be used to avoid an excessive tool load.

In our extensive experimentation presented in [3], trochoid cycles was subject to an excessive tool load when $R/r<1.1$. Region C in Figure 6 belongs to the z-cut division region, i.e. it must be repeatedly machined with a smaller z-cut.

Notice that the trochoidal grooving region (Region B) and the z-cut division region (Region C) can be easily recognized from original contour parallel paths by using the medial axis computed for the given contour geometry.

3 CASE STUDY I

3.1 Overview

Two practical case studies of 2-1/2 dimensional machining of a cavity mold were conducted to show the effectiveness of the proposed machining strategy when it is applied to high productivity machining using a straight end mill.

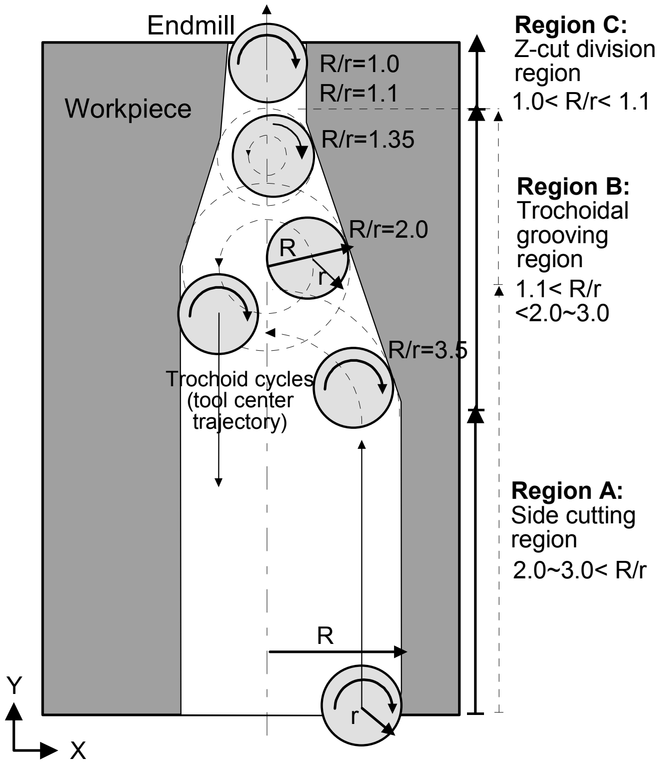


Figure 6. Grooving strategies

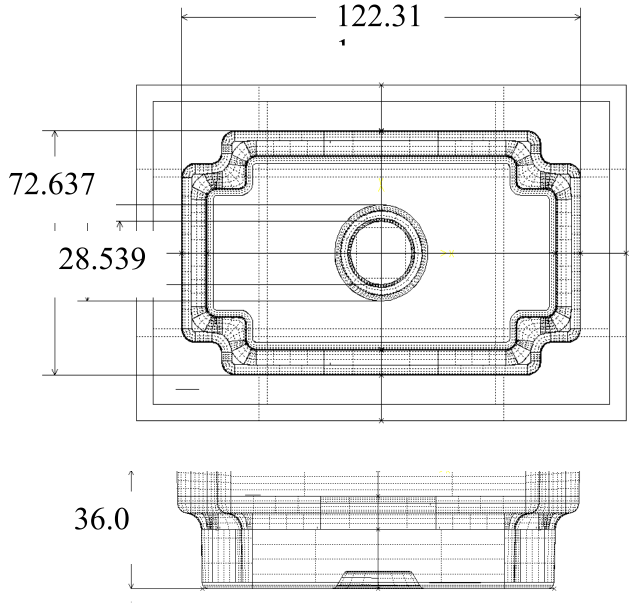


Figure 7. Case study I: Mold geometry (unit: mm)

In the first case study, the machining of a box mold of the geometry shown in Figure 7 is considered. First, this mold is machined by using the tool path given by a commercial CAM software, TOOLS by Graphic Products, Inc., which is well recognized in the industry as one of the best CAM software available for die/mold machining. Then, the tool path is redesigned by using the tool path planning scheme proposed in this paper. Based on actual machining tests, the conventional and proposed tool path planning schemes are compared from various aspects such as the total machining time and the tool damage.

3.2 Proposed machining strategy with a straight end mill

Table 1 summarizes the machining procedure designed based on the scheme proposed in this paper.

Table 1. Machining procedure (Proposed machining strategy)

Step	Geometry	Types of machining (end mill)
1	Hole	Helical boring (ball)
2	Hole expansion	Spiral hole expansion (straight)
3	Slot	Trochoidal grooving (straight) slot width: 20 mm, slot length: 60 mm
4	Side wall	Rough side cutting (straight)
5	Hole	Helical boring (ball)
6	Hole expansion	Spiral hole expansion (straight)
7	Slot	Trochoidal grooving (straight). Slot width: 12 mm, slot length: 800 mm.
8	Side wall	Rough side cutting (straight)
9	Side wall	Intermediate-rough side cutting (straight)

Note that only rough and intermediate-rough cutting processes are considered in the case studies presented in this paper. A straight end mill of the diameter of 10 mm is used in all steps except for a helical boring, where a ball end mill is used. The cavity is divided into four layers in the z-direction. In rough cutting processes, the steps (1)~(4) in Table 1 are repeated for the first three layers with the axial depth of cut, A_d, of 10.0 mm. The fourth layer is machined by the steps (5)~(9) with A_d=5.0 mm (intermediate-rough cutting process).

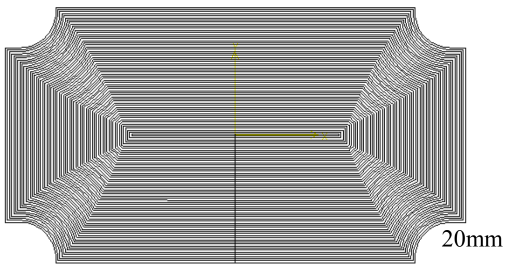
Figure 8 shows contour parallel tool paths for the first and fourth layers (steps (3) and (4)). Figure 9 shows the tool paths designed based on the proposed scheme. In Figure 8 (a), the innermost path yields to a full immersion slotting. Trochoidal grooving is inserted to remove this region. In Figure 8 (b), trochoid cycles are inserted along the selected branches of the medial axis. Figure 10 depicts critical cutting regions that yield to the tool engagement angle larger than 40 degrees. Although the branches of the medial axis connected to corners of the contour also constitute the critical cutting region, trochoid cycles are not inserted there. The tool load variation on these branches can be avoided by the feedrate optimization [3]. It should be noted that, at this stage, such a judgment cannot be automatically made by our tool path planning engine. Fully automated insertion of trochoidal grooving will be left for our future research.

Table 3 shows machining conditions in each step shown in Table 2. Machining conditions are designed based on our machining database.

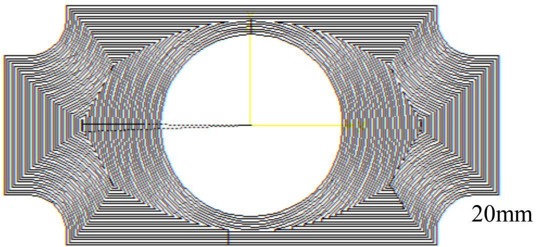
3.3 Conventional machining strategy with a ball end mill

An expert operator designed a machining strategy by using *TOOLS*. In this case, all the processes are machined by using a ball end mill of the diameter of 5 mm. Since a ball end mill is used, the axial depth of cut is set to 0.6 mm, i.e. the z-direction depth of the pocket is divided into 58 layers.

Basically, contour parallel paths are used in all layers. In practice, however, it is quite difficult to machine hardened steel all by contour parallel paths. The latest CAM software such as *TOOLS* are capable of modifying contour parallel paths to avoid an excessive tool load to some extent. For example, the tool path designed by *TOOLS* for the last (58^{th}) layer is shown in Figure 11. Circular paths are inserted in the original path such that the machining of a sharp corner can be divided into two steps [5]. That is, the tool first moves along the circular path to machine the corner with the half radial depth of cut, and then machine it again along the original path.

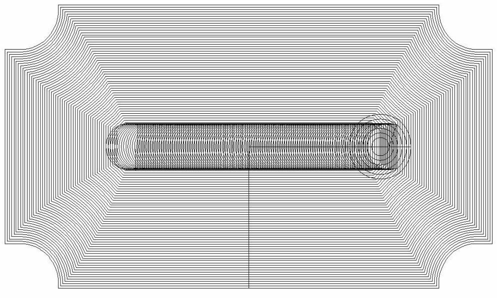


(a) first layer

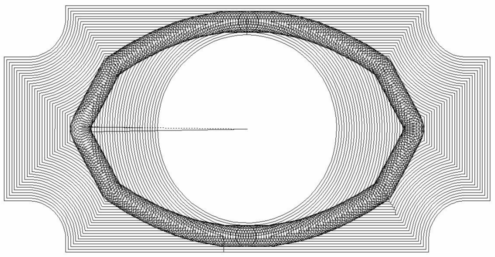


(b) fourth layer

Figure 8. Contour parallel tool paths



(a) first layer



(b) fourth layer

Figure 9. Proposed machining strategy

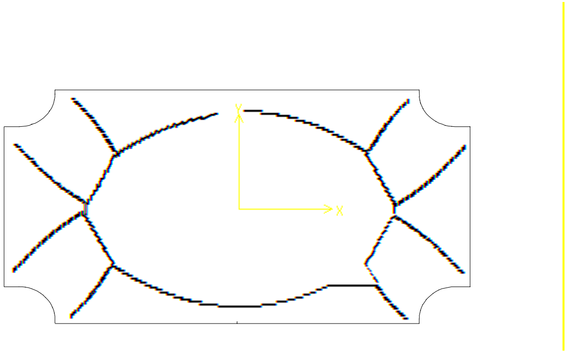


Figure 10. Critical cutting regions on contour paralle paths in the fourth layer

Table 2. Machining conditions (Proposed machining strategy)

(1) (5) Helical boring by a ball end mill	
Tool	(Al, Ti, S)N-coated sintered carbide ball endmill, R5, 2 flutes
Spindle speed	2,800 min^{-1}
Feedrate	0.05 mm/tooth
Axial depth of cut	0.6 mm
Radial depth of cut	0 ~ 10 mm
Tool extension	40 mm
(2) (6) Hole expansion by a straight end mill	
Tool	(Al, Ti, S)N-coated sintered carbide straight endmill, ϕ10mm, 6 flutes
Spindle speed	4,800 min^{-1}
Feedrate	0.1 mm/tooth
Axial depth of cut	(2) 10 mm, , (6) 5 mm
Radial depth of cut	0.5 mm
Tool extension	40 mm
(3) (7) Trochoidal grooving by a straight end mill	
Tool	(Al, Ti, S)N-coated sintered carbide straight endmill, ϕ10mm, 6 flutes
Spindle speed	4,800 min^{-1}
Feedrate	0.05 ~ 0.15 mm/tooth
Axial depth of cut	(3) 10 mm, , (7) 5 mm
Radial depth of cut	0 ~ 0.5 mm
Tool extension	40 mm
Groove width	12, 20 mm
Groove length	800, 60 mm
(4) (8) Rough side cutting by a straight end mill	
Tool	(Al, Ti, S)N-coated sintered carbide straight endmill, ϕ10mm, 6 flutes
Spindle speed	4,800 min^{-1}
Feedrate	0.1 mm/tooth
Axial depth of cut	(2) 10 mm, , (6) 5 mm
Radial depth of cut	0.5 mm
Tool extension	40 mm
(9) Intermediate-rough side cutting by a straight end mill	
Tool	(Al, Ti, S)N-coated sintered carbide straight endmill, ϕ10mm, 6 flutes
Spindle speed	9,600 min^{-1}
Feedrate	0.1 mm/tooth
Axial depth of cut	1 ~ 9 mm
Radial depth of cut	0.5 mm
Tool extension	40 mm

Table 3. Machining conditions (Conventional machining strategy)

All layers	
Tool	(Al, Ti, S)N-coated sintered carbide ball endmill, R5, 2 flutes
Spindle speed	4,800 min^{-1}
Feedrate	0.05 mm/tooth
Axial depth of cut	0.6 mm
Radial depth of cut	3.5 mm
Tool extension	40 mm

Table 4 shows machining conditions in the conventional machining strategy.

3.4 *Experimental setup*

A vertical-type machining center, VM4-II by OKK Corp., was used in machining tests. The workpiece material is hardened die steel, SKD61, of the hardness HRC53. Its initial dimensions are 150mm× 150mm× 60mm. No coolant was used. Only oil air mist lubrication (0.5 Mpa) was provided near the cutting point.

3.5 *Machining results*

Table 5 compares the machining time and the total cutting length in both cases. Compared to the conventional machining strategy with a ball end mill, the proposed strategy shortened the total machining time by 9 minutes (21%).

Figure 12 compares the tool wear in both cases when all the machining processes are finished. Under the proposed strategy, the tool only showed small nor-

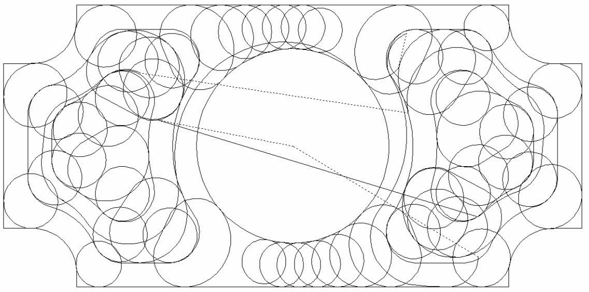


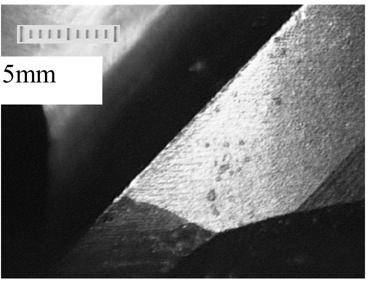
Figure 11. Tool paths generated by TOOLS for the first layer

Table 4. Comparison of machining time and cutting length

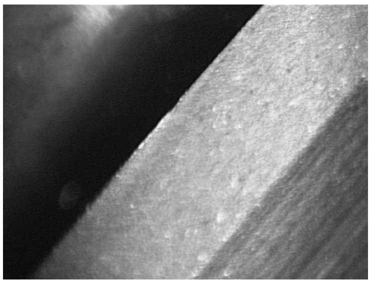
	Proposed strategy		Conventional strategy
Tool	ϕ10mm straight endmill		R5 ball endmill
Machining time	Helical boring Hole expansion: Rough side cutting Interm. side cutting	3’30’’ 4’00’’ 23’18’’ 3’03’’	Contour parallel rough cutting: 42’47’’
Total time		33’51’’	42’47’’
Cutting length		56.07 m	153.9 m

Table 5. Machining procedure (Proposed machining strategy)

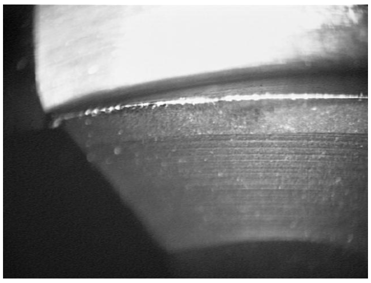
Step	Geometry	Types of machining (end mill)
1	Two holes	Helical boring (ball)
2	Two hole expansion	Spiral hole expansion (straight)
3	Slot	Trochoidal grooving of variable radius (12 ~ 20mm) (straight)
4	Side wall	Sside cutting (straight)



(a-1) Straight endmill (tool tip)



(a-2) Straight endmill (side edge)



(b) Ball endmill

Figure 12. Comparison of tool wear

mal wear (V_b=0.04mm). In the conventional strategy case, the wear was slightly larger (V_b=0.1mm) and a very small chipping was observed.

With respect to the total cutting volume, as well as the progress of tool wear, the machining results of the two strategies did not differ much. Shorter machining time indicates the effectiveness of the proposed strategy.

4 CASE STUDY II

4.1 Overview

In the second case study, a cavity mold of an iron shown in Figure 13 is considered. Similarly as in the first case study, two machining strategies, i.e. the proposed strategy with a straight end mill and the conventional strategy with a ball end mill designed by using *TOOLS*, are compared.

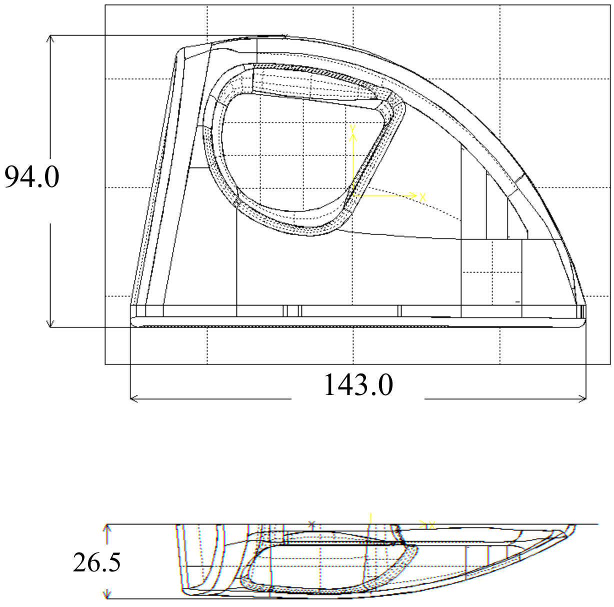


Figure 13. Case Study II: Mold geometry

4.2 Proposed machining strategy with a straight end mill

Table 6 summarizes the machining procedure designed based on the scheme proposed in this paper. A straight end mill of the diameter of 10 mm is used in all steps except for a helical boring. Notice that the bottom surface of the cavity is slightly slanted. Therefore, it is not favorable to set the axial depth of cut too large, since it leaves a large leftover volume to intermediate- rough cutting processes. In this case study, we set the axial depth of cut at 5.0mm at each layer, which is half of the one in the previous case study. Total five layers will be machined.

Figure 14 shows contour parallel tool paths for the first layer. Figure 15 shows tool paths designed based on the proposed scheme. Trochoidal grooving is inserted in critical cutting regions. The upper-left slot part is machined only by trochoid cycles of variable radius. Notice that Region A is too narrow to insert trochoid cycles. Since *R/r* becomes less than 1.2 (see Section 2.3), we judged that this region belongs to the z-cut division region, i.e. this region must be repeatedly machined with a smaller axial depth of cut (0.5 mm).

Table 7 shows machining conditions in each step shown in Table 6. Machining conditions are designed based on our machining database.

4.3 Conventional machining strategy with a ball end mill

Similarly as in the previous case study, an expert operator designed a machining strategy by using the

Table 6. Machining conditions (Proposed machining strategy)

(1) Helical boring by a ball end mill	
Tool	(Al, Ti, S)N-coated sintered carbide ball endmill, R5, 2 flutes
Spindle speed	2,800 min^{-1}
Feedrate	0.05 mm/tooth
Axial depth of cut	0.6 mm
Radial depth of cut	0 ~ 10 mm
Tool extension	30 mm
(2) Hole expansion by a straight end mill	
Tool	(Al, Ti, S)N-coated sintered carbide straight endmill, ϕ10mm, 6 flutes
Spindle speed	4,800 min^{-1}
Feedrate	0.1 mm/tooth
Axial depth of cut	5.0 mm
Radial depth of cut	5.0 mm
Tool extension	40 mm
(3) Trochoidal grooving by a straight end mill (including z-cut division region)	
Tool	(Al, Ti, S)N-coated sintered carbide straight endmill, ϕ10mm, 6 flutes
Spindle speed	2,400 ~ 9,600 min^{-1}
Feedrate	0.05 ~ 0.08 mm/tooth
Axial depth of cut	5.0 mm (0.5mm)
Radial depth of cut	0.5 mm, (10.0mm)
Tool extension	30 mm
(4) Rough side cutting by a straight end mill	
Tool	(Al, Ti, S)N-coated sintered carbide straight endmill, ϕ10mm, 6 flutes
Spindle speed	9,600 min^{-1}
Feedrate	0.08 mm/tooth
Axial depth of cut	5.0 mm
Radial depth of cut	0.5 mm
Tool extension	30 mm

TOOLS. In this case, all the processes are machined by using a ball end mill of the diameter of 5 mm. The axial depth of cut is set to 0.6 mm.

Table 8 shows machining conditions used in the conventional machining strategy.

4.4 Machining results

The same machining center and the same workpiece were used for machining tests. Figure 16 shows the workpieces when all the rough-cutting processes are finished.

Table 9 compares the machining time and the total cutting length between both cases. Compared to the conventional machining strategy with a ball end mill, the proposed strategy shortened the total machining time by 4’36’’.

4.5 Discussion

On mold geometry :

The mold in the second case study has a slightly slanted bottom surface, and the pocket depth is relatively small (25 mm) with respect to the tool diameter. In such a case, the proposed machining scheme with a straight end mill cannot exhibit its potential advantages to a full extent, since the axial depth of cut must be limited to some level to avoid a large leftover volume. Figure 16 indicates that there are

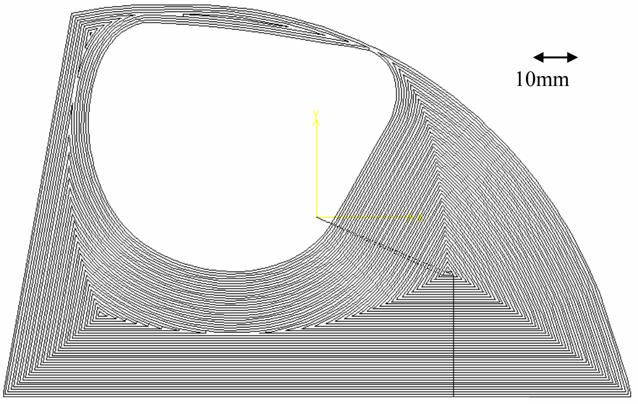


Figure 14. Contour parallel tool paths

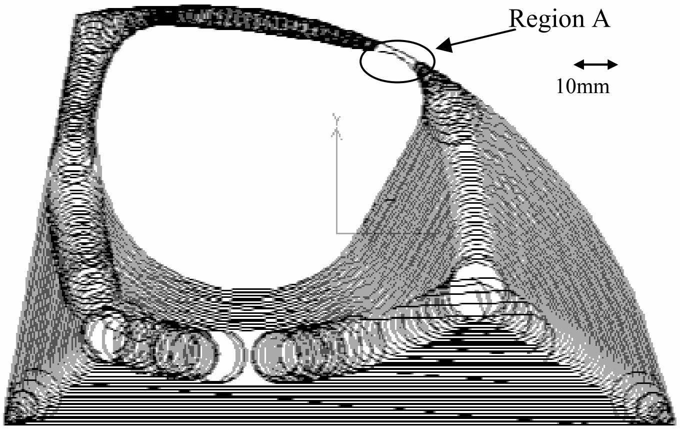


Figure 15. Tool paths with trochoidal grooving

Table 7. Machining conditions (Conventional strategy)

All layers	
Tool	(Al, Ti, S)N-coated sintered carbide ball endmill, R5, 2 flutes
Spindle speed	10,000 min^{-1}
Feedrate	0.3 mm/tooth
Axial depth of cut	0.6 mm
Radial depth of cut	4.0 mm
Tool extension	30 mm

Table 8. Comparison of machining time and cutting length

	Proposed strategy		Conventional strategy
Tool	ϕ10mm straight endmill		R5 ball endmill
Machining time	Helical boring Hole expansion: Side cutting	4’48’’ 2’06’’ 23’33’’	Contour parallel rough cutting: 35’05’’
Total time		30’27’’	35’05’’
Cutting length		54.3 m	106.4 m

(a) By the proposed machining strategy

(b) By the conventional strategy

Figure 16. The workpieces machined by the two strategies

more leftover volume on the bottom surface in the proposed machining strategy case. Although the conventional strategy with a ball end mill took slightly more machining time, the machining time for intermediate-rough cutting processes will be less than that in the proposed strategy case.

The cavity in the first case study has a flat bottom and almost vertical side walls. In such a case, the proposed machining strategy exhibits larger improvement in the machining productivity.

On the expertise of an operator :

It should be noted that the conventional strategy requires an expert operator to carefully design machining conditions in order to obtain the machining results shown in two case studies. When the proposed strategy is employed, the design of machining conditions becomes much easier. We have developed the database of machining conditions for the proposed strategy. Two case studies showed its validity as well.

5 CONCLUSIONS

Rough cutting by using a straight end mill instead of a ball end mill has been considered as a key technology to further enhance the productivity of die and mold manufacturing. A straight endmill allows much larger axial depth of cut, which significantly reduces the number of layers in the z-direction in 2-1/2 dimensional machining. In two-dimensional machining by a straight end mill, however, the tool is typically subject to a much higher tool load. Therefore, very careful design of tool paths and machining conditions is crucial. The proposed tool path planning scheme using trochoidal grooving for critical cutting regions is quite effective to perform a safe machining without requiring profound knowledge and experiences of an expert operator. Two case studies showed the effectiveness of the proposed tool path planning scheme to enhance the overall productivity without sacrificing the tool life in high speed machining by using a straight end mill.

REFERENCES

[1] Ibaraki, S., Yamaji, I., Kakino, Y. & Nishida, S. 2003. 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 –, To be presented at ICAM2003.

[2] Ibaraki, S., Sakahira, M., Matsubara, A., & Kakino, Y. 2002. Simulation and Control of Cutting Forces in 2-1/2 Dimensional End Milling Processes, *Proc. of 6th Int'l Conf. on Progress of Machining Technology*, pp. 727-732.

[3] Adachi, Y. 2003. The effect of cutting heat on the tool life in die and mold manufacturing, Master Thesis. Kyoto University (in Japanese).

[4] http://www.graphicproducts.co.jp

[5] Iwabe, H., Fujii, Y., Saito, K., and Kishinami, T. 1989. Study on Corner Cut by End Mill – Analysis of Cutting Mechanism and New Cutting Method of Inside Corner. *Journal of JSPE*, 55(5): 841-846 (in Japanese).