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CONSTANT ENGAGEMENT TOOL PATH GENERATION FOR TWO-DIMENSIONAL END MILLING

Soichi Ibaraki, Daisaku Ikeda, Iwao Yamaji, Atsushi Matsubara, Yoishiaki Kakino
Department of Precision Engineering, Kyoto University
Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501, Japan
Email: ibaraki@prec.kyoto-u.ac.jp

Susumu Nishida
Manufacturing Technology Institute, Inc.,
Chiba 261-0023, Japan

ABSTRACT

On a contour-parallel tool path that is often used in die/mold machining, there are many regions where the tool is subject to a significant variation of cutting forces. In a finishing process, such a variation of cutting forces easily causes the degradation of machining accuracy and surface finish. This paper proposes algorithms to generate offset tool paths that maintain a constant cutting engagement in a 2-1/2 dimensional end milling. By maintaining the cutting engagement angle constant, the cutting force can be regulated approximately constant, which significantly reduces the variation of tool deflection, and then improves the machining accuracy. The validity of the proposed tool path generation schemes is investigated by machining experiments on hardened steel.

Key words: End milling, tool path, offset, contour parallel paths, cutting engagement angle, cutting force.

1 Introduction

For the machining of dies and molds, CL data (cutter location data) are generated by using commercial CAD/CAM software in most cases. Commercial CAD/CAM software available in today's market adopt sophisticated tool path generation routines for both contour-parallel and direction-parallel paths. They do not, however, pay much attention to issues related to machining processes; their only focus is on the generation of tool paths that can geometrically remove the required volume. In recent years, technical development in tools such as the introduction of (Al,Ti)N-coated sintered carbide tools has made it possible to directly machine pre-hardened steel of the hardness up to HRC53. Particularly in the machining of such a hardened material, a contour-parallel tool path often causes a problem. As a result, an operator's expertise is crucial in careful design of machining conditions and possibly manual modification of CL data in real-world die/mold manufacturing.

Contour-parallel tool paths inevitably introduces the variation of cutter engagement depending on the path geometry, which causes the variation of cutting forces in the machining. Kramer [1] presented that regions of excessive engagement can be detected by calculating the engagement angle. As illustrated in Figure 1, the engagement angle, θ, is the parameter defined by the geometrical interaction of tool and workpiece. It can be easily understood that an abrupt increase in the cutter load at a corner can be modeled as an abrupt increase of the engagement angle [2]. Clearly, the variation in cutting forces causes the variation in the tool deflection, which manifests as dimensional and surface errors [3].

To avoid the variation of cutting forces, many researchers have been studying feedrate control schemes. For example, some latest commercial CAM software adopt a simple feedrate optimization scheme such that the material removal rate is regulated constant. There have been relatively little work done to explicitly modify tool paths. Iwabe et al. [4] presented the insertion of an additional circular-arc loop at a convex corner to keep cutter engagement below the prescribed limit. This strategy is also adopted in some latest commercial CAM software. Yamaji et al. [5] presented a tool path planning scheme to remove critical cutting regions by trochoidal grooving. These approaches are effective to avoid an excessive tool load mainly in rough cutting.

A notably unique approach was proposed by Stori and Wright [6], where an offset tool path is modified such that the engagement angle is always maintained constant. The algorithm can be, however, applied only to convex contours, which is too strong a restriction for practical implementation. Fur-

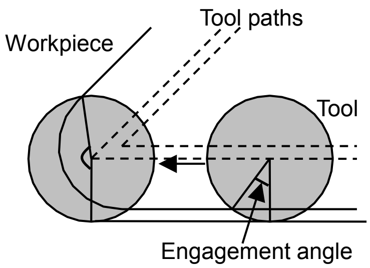


Figure 1. Definition of the engagement angle

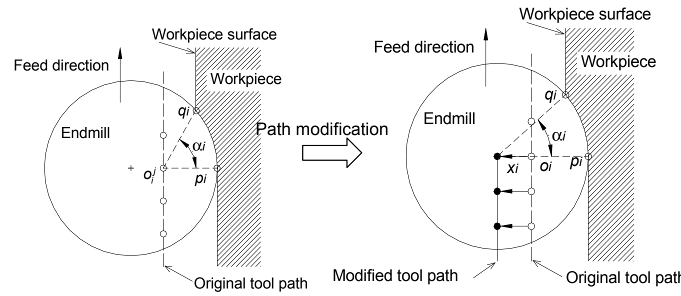


Figure 2. Algorithms I

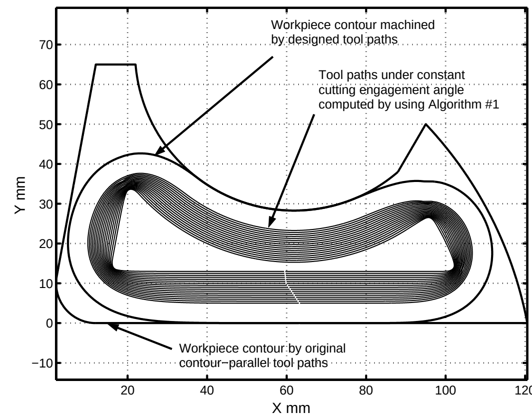


Figure 3. An example of constant engagement tool paths computed by using Algorithm I

thermore, when it is applied to a spiral-out tool path, it leaves leftover material and requires an additional machining to remove excess corner material. Although this approach may be justified in the application to rough cutting where efficient material removal is the primary objective, it cannot be applied to a finishing process.

As an extension of Stori's algorithm [6], this paper proposes a tool path modification scheme for constant engagement such that the final workpiece geometry to be machined can be preserved in the application to a spiral-put tool path. Unlike Stori's algorithm, the proposed algorithm can be applied to any two-dimensional contours. The effectiveness of the proposed tool path generation algorithm applied to a finishing path by a straight end mill to reduce the dimensional error of the machined surface is experimentally investigated.

2 Algorithms for Constant Engagement Tool Path Generation

2.1 Algorithm I: Forward Tool Path Generation

2.1.1 Algorithm Given the planar curve representing the final contour to be cut, the objective of Algorithm 1 is to modify an original contour parallel tool path such that the cutting engagement angle is regulated at the given desired level throughout. Figure 2 illustrates the proposed algorithm. Suppose that the tool radius, r, a sequence of points representing an initial tool path (a contour parallel tool path), $o_i \in \mathbb{R}^2$ ($i = 1 \sim N$), and a sequence of points representing the previously cut surface, are given. At each step, the tool center location, o_i, is moved to the direction normal to the tool path by the distance x_i such that the engagement angle, α_i, is regulated to the given desired level, α_i^*, by the following algorithm:

1. Move the original tool center location, o_i, to o_i^0 by the initial modification distance x_{i-1}. Compute the engagement angle α_i^0 for o_i^0.
2. Based on an error between α_i^0 and the desired level, α_i^*, perform one step of the Newton method as follows:

$$\begin{aligned} e_i &= \alpha_i^* - \alpha_i^0 \\ x_i &= x_{i-1} - \frac{e_i}{\frac{de_i}{dx_i}} \end{aligned} \quad (1)$$

3. Set $i = i+1$ and repeat from Step 1 till $i = N$.

Note that the Newton step is not repeated more than once to simply shorten the computation time. The engagement angle, α_i, can be computed from the geometric interaction of the tool and the workpiece surface. In Step 2, the gradient $\frac{de_i}{dx_i}$ is computed only numerically by using this function. Unlike Stori's algorithm [6], the present approach does not mathematically guarantee the convergence to optimal solutions. In practice, however, we have verified that the present algorithm gives the same trajectory in most cases. An advantage of the present algorithm is that it can be applied to an arbitrary contour geometry, unlike the Stori's algorithm [6], which is restricted to convex contours.

2.1.2 Application to Pocket Machining Consider the application of the present algorithm to a spiral-out tool path for pocketing. By applying Algorithm I, contour parallel tool paths are modified from the innermost path to the outermost path. Figure 3 shows an example of constant engagement tool paths computed by using Algorithm I. As is clear from the figure, the outermost path is subject to the largest modification, and thus the required pocket contour cannot be made. To achieve the required pocket geometry, additional machining will be required to remove excess corner materials. Although such an approach may be justified in cases where efficient ma-

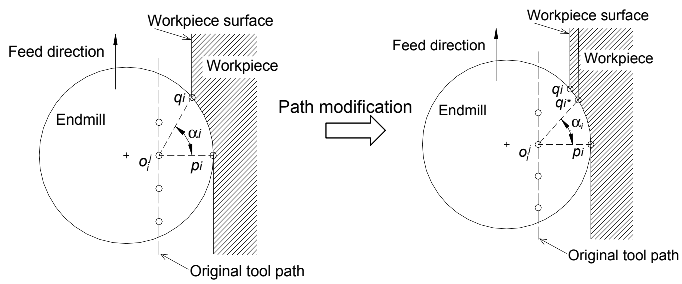


Figure 4. Algorithms II

terial removal is the primary objective, it is not practical in most cases. Note that this approach is effective when applied to spiral-in tool paths, as has been shown by Stori and Wright [6].

2.2 Algorithm II: Backward Tool Path Generation

This section presents an extension of Algorithm I such that the final pocket geometry is preserved when is applied to a spiral-out tool path. Figure 4 illustrates its concept. This algorithm modifies the precut workpiece surface, instead of the tool path itself, such that the engagement angle is regulated at the desired value. The modification of the precut workpiece can be done by the modification of the previous inner path. When one cycle of the tool path, $o_i^j \in \mathbb{R}^2$ ($i = 1 \sim N_j$), is given, the previous inner tool path, $o_i^{j-1} \in \mathbb{R}^2$ ($i = 1 \sim N_{j-1}$) is modified as follows:

1. For the given tool center location o_i^j, compute the intersection of the tool circumference with the newly generated offset surface, $p_i \in \mathbb{R}^2$ (see Fig. 4).
2. Compute the intersection of the tool circumference with the previous surface, $q_i^* \in \mathbb{R}^2$, such that the engagement angle α_i becomes the given desired value.
3. Set $i = i+1$ and repeat Steps 1 and 2 till $i = N$.
4. By offsetting q_i^* ($i = 1 \sim N_j$) to the inside by the tool radius, the inner tool path, o_i^{j-1} ($i = 1 \sim N_{j-1}$) is given.

Figure 5 shows an example of tool path generation by using Algorithm II. Path 1 and Path 2 are original contour parallel tool paths. Path 1 is first machined and Path 2 is a finishing path. By applying Algorithm II, Path 1 is modified into Path 1-a such that the engagement angle along Path 2 is kept constant.

3 Experimental Validation

Machining experiments were conducted to validate the effectiveness of a constant engagement offset tool path to reduce the variation of cutting forces, and to improve the machining accuracy. A finishing path for a simple corner geometry shown in Fig. 6 was machined by the following three strategies:

1) **Strategy 1** (original tool path, constant feedrate): A contour-parallel path is used as the intermediate-finishing path, prior to the finishing path. The feedrate is constant on both paths.

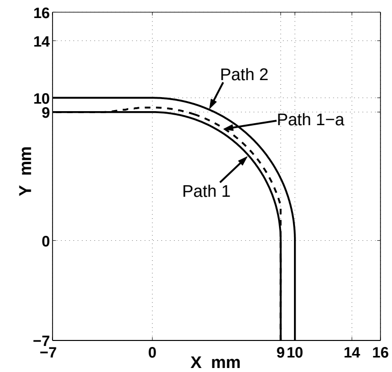


Figure 5. An example of tool path generation by Algorithm II

2) **Strategy 2** (original tool path, variable feedrate): A contour-parallel path is used as the intermediate-finishing path. The feedrate on the finishing path is regulated such the feed per tooth at actual cutting point is kept constant. This simple feedrate optimization approach is known to be effective to suppress the variation of cutting forces [7].
3) **Strategy 3** (constant engagement tool path, constant feedrate): The intermediate-finishing path is generated by using Algorithm 2. The feedrate is constant on both paths.

In all the cases, an (Al, Ti)N-coated sintered carbide straight end mill (diameter: 10 mm, 4 flutes) was used. The workpiece material was die steel, JIS SKD61 (HRC53). Table 1 shows machining conditions. In Strategies 1 and 2, the engagement angle, α, increases from 11.5° on the straight part to 19° on the circular part. By applying Algorithm II, the intermediate-finishing path prior to the finishing path is modified such that engagement angle along the finishing path is kept at 11.5° throughout. Recall that the finishing path itself is the same in all the cases.

Figure 7 shows the comparison of the cutting force in the XY plane on the finishing path measured by using a dynamometer. Under Strategy 1, the cutting force increases at the corner arc. By using the modified path (Strategy 3), the variation of cutting force is suppressed within 17 N. The variation of cutting force can be also reduced by the feedrate regulation (Strategy 2). Figure 8 compares a geometric error profile of the workpiece surface measured by using a CCM. Taking Surface A and B in Fig. 6 as reference surfaces, an error from the nominal trajectory is plotted. In (a) Strategy 1, there is a leftover of the depth of 14 μm at maximum at the corner arc. By applying the constant engagement tool path (Strategy 3), the geometrical surface error at the corner arc was significantly reduced. As shown in Fig. 8(b), the feedrate regulation is also effective to improve the machining accuracy. However, its effectiveness is more strongly influenced by the machine's servo control performance. For example, errors observed at an entry and an exit of the corner arc in Fig. 8(b) are caused by the servo delay in

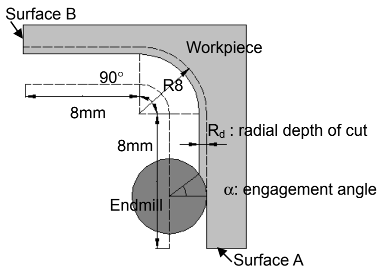


Figure 6. A schematic view of cutting experiment

Table 1. Machining conditions in the machining of the finishing path

Spindle speed	4,775 min^{-1}
Cutting direction	Down cutting
Axial depth of cut	5 mm
Coolant	Dry air
Feed per tooth	Strategies 1 and 3: 0.04 mm/tooth Strategy 2: 0.04 mm/tooth in the straight part, 0.015 mm/tooth in the circular part
Radial depth of cut	Strategies 1 and 2: 0.1 mm Strategy 3: 0.1 $\sim$ 0.04 mm

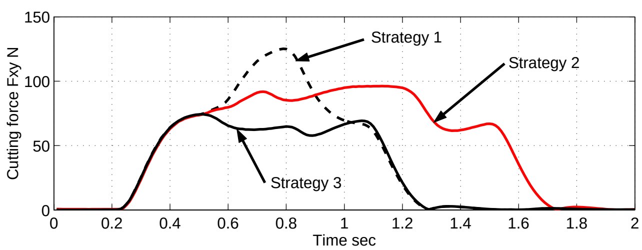


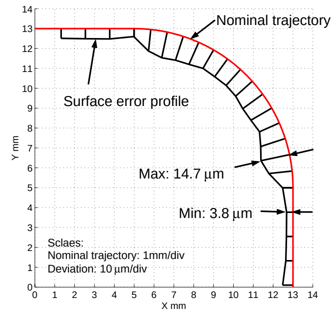
Figure 7. Comparison of cutting force on the finishing path

velocity control. In a high-speed machining, and/or when a machine does not have sufficient velocity control performance, this problem possibly becomes more critical.

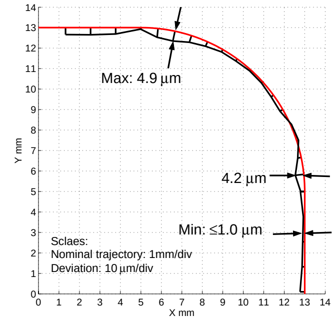
4 Conclusion

In this paper, two approaches to generate tool paths subject to a constant engagement angle were proposed. In the application to a spiral-out offset tool path for pocket machining, Algorithm II can generate a constant engagement tool path while preserving the final workpiece contour to be cut. Algorithm I can be applied to modify spiral-in offset tool paths. From machining tests, the following conclusions are drawn:

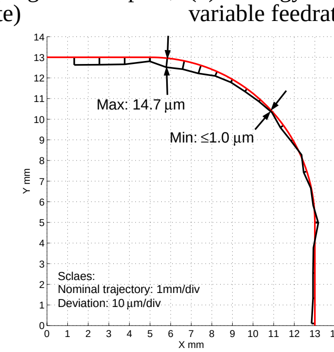
1) By using a constant engagement tool path, the cutting force can be regulated approximately at a constant level.
2) By applying Algorithm II to a intermediate-finishing path, the geometrical surface accuracy was significantly improved. It can be potentially applied to enhance the machining productivity without sacrificing the machining accuracy.



(a) Strategy 1 (original tool path, constant feedrate)



(b) Strategy 2 (original tool path, variable feedrate)



(c) Strategy 3 (constant engagement tool path, constant feedrate)

Figure 8. Geometrical surface error profiles measured by using a coordinate measuring machine

In practical die and mold machining, finishing processes are mostly done by using a ball end mill. The extension of the present approaches to the finishing by a ball end mill is left for our future research.

REFERENCES

[1] Kramer, T. R. "Pocket Milling with Tool Engagement Detection," *J. of Manufacturing Systems*, 11, 2 (1992), 114–123.
[2] Choy H. S., Chan K. W., "Modeling Cutter Swept Angle at Cornering Cut," *Int. J. of CAD/CAM*, 3, 1(2003), 1–12.
[3] Li, Y., Iwabe, H. and Fujii, Y. "Study on improvement of machining accuracy in cornering cut with end mill," *JSME Int. J. Series III*, 35, 1 (1992).
[4] Iwabe, H., Fujii, Y., Saito, K. and Kishinami, T., "Study on corner cut by end mill," *Int. J. of JSPE*, 28(8).
[5] Yamaji, I., Ibaraki, S., Kakino, Y., Nishida, S., "Tool path planning using trochoid cycles for hardened steel in die and mold manufacturing (2nd report) – Tool path planning to avoid an excessive tool load –," *Proc. of Int.Conf. on Agile Manufacturing*, (2003), 443–450.
[6] Stori, J. A. and Wright, P. K. "Constant Engagement Tool Path Generation for Convex Geometries," *J. of Manuf. Sys.*, 19, 3(2000), 172–184.
[7] Nishida, S., Ohtsuka, Y., Yamaji, I., Kakino, Y., Ibaraki, S., and Matsubara, A., "The Improvement of Productivity and Quality in Die/Mold Machining by Constant Feedrate Control at the Cutting Point," to be presented at *2004 Japan-USA Symp. on Flexible Automation*, (2004).