Proceedings of 2006 ISFA
2006 International Symposium on Flexible Automation
Osaka, Japan, July 10-12, 2006

0041-a(S)

A TOOL PATH MODIFICATION APPROACH TO CUTTING ENGAGEMENT REGULATION FOR THE IMPROVEMENT OF MACHINING ACCURACY IN 2.5D END MILLING

M. Sharif Uddin, Soichi Ibaraki *, Atsushi Matsubara
Department of Micro Engineering, Kyoto University
Yoshida-honmachi, Sakyo-ku, Kyoto 606-851, Japan
*ibaraki@prec.Kyoto-u.ac.jp

Susumu Nishida
Manufacturing Technology Institute, Inc.,
Ebisu 1-19-19, Shibuya-ku, Tokyo 150-0013, Japan

Yoshiaki Kakino
Kakino Research Institute
Enpukuji-cho 324-1, Nakagyo-ku, Kyoto 604-8175, Japan

ABSTRACT

This paper introduces an algorithm to generate a new offset tool path, which is able to regulate cutting engagement with workpiece at a desired value. The inherent idea of the proposed algorithm is to modify the previous tool path trajectory to regulate the pre-cut surface trajectory for the finishing path such that the finishing path is subject to the desired engagement angle. The expectation is that by regulating the cutting engagement angle along the tool path trajectory, the cutting force can be controlled at any desirable value, which will potentially reduce variation of tool deflection, thus improving geometric accuracy of machined workpiece. In this study, an application of the proposed algorithm for tool path modification is demonstrated to a case with the feedrate optimization scheme. Cutting experiments on the core workpiece of hardened steel material are carried out to verify the significance of the proposed approach.

Keywords: Contour milling, cutting engagement angle, tool path modification, cutting force, geometric accuracy

1 INTRODUCTION

When the mechanics of real machining process is considered, conventional contour parallel paths possess inherent problems in the actual machining. The critical cutting problem associated with them is significantly varying cutting engagement that causes the change in cutter load and tool deflection, amplifies tool wear and consequently impairs part quality. Shown in Fig.1 is how cutting engagement angle varies depending on the geometry of the tool path. From the figure, it can be realized that cutting engagement angle is one of dominant instantaneous process parameters, which determines cutting load, tool deflection and process stability.

To avoid an excessive cutting load that may cause tool damage, or to secure the required machining accuracy by limiting tool deflection, one must very carefully choose various machining conditions in contour parallel machining. This is particularly the case in machining of hardened materials, which is now common in die and mold manufacturing. To avoid the tool damage, a process planner is often forced to select feedrates and cutting speeds conservatively for a worst-case situation. To enhance the machining productivity without sacrificing tool life, various research efforts have been made. A major and widely used approach to control cutting engagement

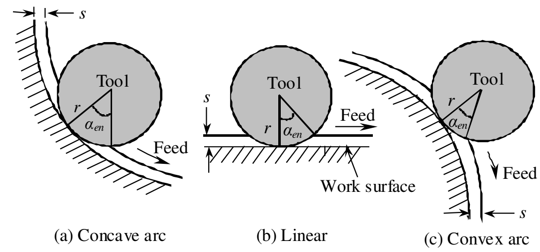


Figure 1. Cutting engagement in 2.5D end milling

or cutting force is adjusting feedrate adaptively [Fussel et al. (2001)]. In this case, feedrates are scheduled based on several regimes of engagement or continuously varied to keep constant material removal rate (MRR).

However, there has been relatively little attempts made to explicitly modify tool path trajectory, such that varying cutting engagement is suppressed or regulated. Iwabe et al. (1989) proposed to add additional circular arcs to regulate the prescribed cutting engagement in convex corner cutting. Recently Stori and Wright (2000) proposed a notable approach to offset tool path modification for keeping constant engagement in convex arc cutting. However, since the algorithm modifies the final path trajectory (i.e. finishing path) to keep constant engagement on it, the modified tool path no longer removes required geometry, leaving excess material in corner cutting. Hence, although this approach may be justified in the application of rough cutting where efficient material removal is of sole interest, it is practically not possible to be applied to a finishing process.

This paper presents an algorithm to generate a new offset tool path trajectory, which will regulate cutting engagement at a desired value on the finishing path. Unlike the approach by Stori and Wright (2000), the inherent idea of the proposed algorithm is to modify the semi-finishing tool path trajectory with an aim that a desired engagement is regulated in the finishing path while the geometry of the finishing path itself is preserved. As an application example, the proposed algorithm for tool path modification is applied to a case with the feedrate optimization scheme where feedrate at tool center is varied to keep constant feedrate at cutting point. Cutting experiments on the core workpiece of hardened steel material are carried out to verify the significance of the proposed approach.

2 PROPOSED APPROACH

2.1 Algorithm for tool path modification to regulate cutting engagement

Given an initial planar curve representing the desired geometry of the final contour to be machined, and an original contour-parallel (CP) tool path to achieve the desired contour (referred to as the finishing path hereafter), the main aim of the algorithm is to compute the previous tool path trajectory (the path prior to the finishing path) such that the engagement angle can be regulated at a desired level on the machining along the finishing path trajectory. Figure 2 describes the basic working principle of the proposed algorithm for tool path modification.

Assume that a trajectory of the tool center location in the finishing path, $o_k(i)\in R^2\ (i=1,\ldots,N_k)$, is given by offsetting the final workpiece contour to be machined. As illustrated in Fig. 2, the engagement angle, $\alpha_{en}(i)\in R(i=1,\ldots,N_k)$, is defined by the tool center location, $o_k(i)$, the intersection point of the tool circumference with the newly generated offset surface, $q_k(i)\in R^2(i=1,\ldots,N_k)$, and the intersection point of the tool circumference with the previously cut surface, $p_k(i)\in R^2(i=1,\ldots,N_k)$. The intension of the proposed algorithm is to modify the location of the intersection between the tool circumference and the previously cut surface, $p_k(i)$, to regulate the cutting engagement angle. Since this "precut surface trajectory" is generated by the previous path trajectory (referred to as the semi-finishing path hereafter), the modification of pre-cut surface, $p_k(i)$, can be done by the modification of the trajectory of the tool center location in the semi-finishing path, $o_{k-1}\ (i)\in R^2\ (i=1,\ldots,N_{k-1})$. The detailed algorithm of the computation of new modified offset tool path trajectory, $o_{k-1}\ (i)\in R^2\ (i=1,\ldots,N_{k-1})$ for concave and convex arc milling as shown in Fig. 2 can be summarized into the following steps.

Step1: For the given tool center location, $o_k\ (i)\in (i=1,\ldots,N_k)$, of the finishing path, compute the intersection point of the tool circumference with the newly generated offset surface, $q_k(i)\in R^2(i=1,\ldots,N_k)$, by offsetting $o_k(i)$ to the workpiece's side by the tool radius, r. This operation can written by:

$$q_k(i) = \text{offset}\ (o_k\ (i), +r),\quad \text{where}(i=1,\ldots,N_k) \qquad (1)$$

where the function "offset(o(i),x)" represents the computation of the trajectory that is generated by parallel offsetting the trajectory o(i) by the distance x.

Step2: Compute the intersection point of the tool circumference with the previously cut surface, $p_k^*(i)\in R^2(i=1,\ldots,N_k)$ such that the engagement angle, $\alpha_{en}(i)\in R^2(i=1,\ldots,N_k)$, can be maintained at the desired cutting engagement angle, $\alpha_{en}^*(i)\in R(i=1,\ldots,N_k)$. In other words, find $p_k^*(i)$ such that:

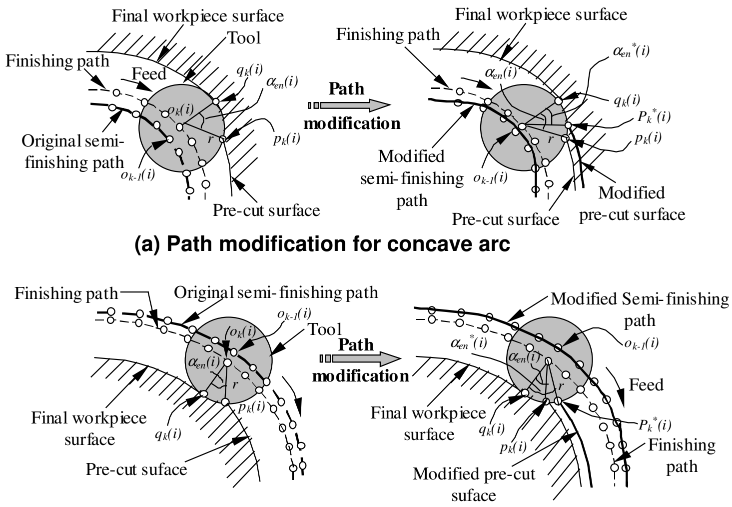
$$\angle\, p_k^*(i)\cdot o_k(i)\cdot q_k(i) = \alpha_{en}^*(i)\quad,\ \text{and}\quad \| p_k^*(i) - o_k(i)\| = r,\ (i=1,\ldots,N_k)$$

Notice that $p_k^*(i)\in R^2\ (i=1,\ldots,N_k)$ defines the trajectory of modified pre-cut surface (see Fig. 2).

Step3: Set $i=i+1$ and repeat the steps (1) and (2) till $i=N_k$.

Step4: Then, by offsetting modified pre-cut surface trajectory, $p_k^*(i)\in R^2(i=1,\ldots,N_k)$ toward the inside for concave arc milling case (Fig. 2(a)) and toward outside for convex arc milling case (Fig. 2(b)) by the tool radius r, compute the modified tool center trajectory of the semi-finishing path, $o_{k-1}(i)\in R^2\ (i=1,\ldots,N_{k-1})$.

$$o_{k-1}\ (i) = \text{offset}\ (p_k^*(i), -r),\ \text{where}\quad (i=1,\ldots,N_k) \qquad (2)$$



(a) Path modification for concave arc

(b) Path modification for convex arc

Figure 2. Concept of the algorithm for tool path modification

The desired engagement angle, $\alpha_{en}^*(i)\in R(i=1,\ldots,N_k)$ along the final tool path trajectory,$o_k(i)\in R^2\ (i=1,\ldots,N_{k-1})$ must be given by considering proper machining conditions for the given tool and the workpiece. In other words, the desired engagement angle, $\alpha_{en}^*(i)\in R(i=1,\ldots,N_k)$ can be defined as the engagement angle which is to be regulated such that an expected cutting force is maintained all the times.

As can be seen in Fig.1, on a concave corner, the cutting engagement angle becomes always larger than a desired value. Thus, for concave arc milling case, the proposed algorithm will modify the trajectory of semi-finishing tool path such that the engagement angle is decreased as shown in Fig. 2(a). On the other hand, for convex arc milling case, the trajectory of semi-finishing tool path will be modified such that the engagement angle is increased as shown in Fig. 2(b).

3 APLICATION OF THE PROPOSED ALGORITHM TO FEEDRATE OPTIMIZATION SCHEME

In 2.5D contour machining, feedrate at the actual cutting point varies even the feedrate at the tool center is kept constant. The variation in feed per tooth at the cutting point naturally causes the variation in the width of cutter marks generated on the machined surface, which often deteriorates the surface quality. To address it, a scheme to regulate the feedrate at tool center such that the feedrate at the cutting point is kept constant has been well known, and it is implemented in some latest CAM software. A constant feedrate at the cutting point generally does not keep the cutting force constant. Using the proposed algorithm as illustrated earlier, the semi-finishing path is modified such that an expected cutting force is regulated efficiently in the finishing path. By applying both the feedrate optimization and the tool path modification, it is expected that both the geometric accuracy and the surface quality of the machined workpiece will be improved.

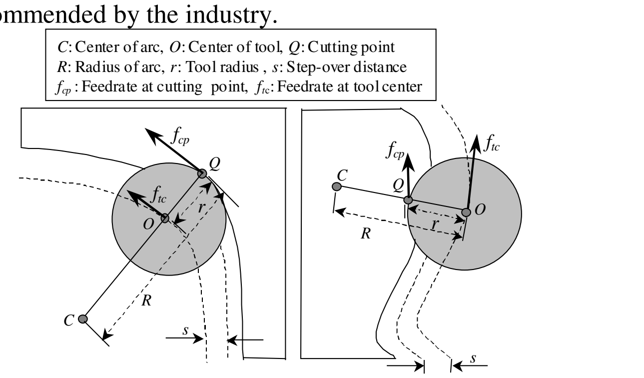
3.1 Definition of feedrate at the cutting point and its regulation

Figure 3 defines the feedrate at the cutting point and feedrate at the tool center for concave and convex arc milling. From the figure, it can be easily understood that feedrate at the cutting point, f_{cp} is totally different from that at the tool center, f_{tc} depending on the geometry of workpiece contour. Note that on most of typical CNCs, the feedrate of the tool must be commanded as the feedrate at tool center. Hence, in order to keep the feedrate at the cutting point, f_{cp} at a constant level, we have varied the feedrate at the tool center, f_{tc}. Assume that the geometry of workpiece contour such as curvature radius, $R(i)$ $(i=1,\ldots,N_k)$ along the finishing path trajectory, is given. Thus, variable feedrate rate at the tool center, $f_{tc}^*(i)\in R(i=1,\ldots,N_k)$ can be optimized as follows:

For concave arc, $f_{tc}^*(i) = f_{cp}.(R(i) - r)/R(i)$ (3)

For convex arc, $f_{tc}^*(i) = f_{cp}.(R(i) + r)/R(i)$ (4)

The desired feedrate at the cutting point, f_{cp} to be kept constant is chosen from the machining database or recommended by the industry.



(a) Concave arc milling (b) Convex arc milling

Figure 3. Definition of feedrate at the cutting point and feedrate at the tool center

3.2 Optimization of cutting engagement angle for constant cutting force regulation

As is mentioned earlier, a constant feedrate at the cutting point does not necessarily keep the cutting force at a constant value. However, in contour machining, regulating cutting force at a desired level is an important concern to reduce tool deflection and thus to enhance the machining accuracy.

When the feedrate at tool center along the finishing tool path trajectory is given by $f_{tc}^*(i)\in R(i=1,\ldots,N_k)$, first a profile of the desired engagement angle is computed such that the cutting force is regulated at the given desired level. In this study, we adopt the cutting force prediction model developed by Otsuka et al. (2001). When the feedrate at the cutting point is fixed, Otsuka's prediction model can be rewritten as:

$$\hat{F} = \beta_0 + \beta_1 .\sin\alpha_{en}(i) + \beta_2.\ \alpha_{en}(i) + \beta_3.(\sin\alpha_{en}(i))^2 + \beta_4.(\alpha_{en}(i))^2 + \beta_5.\ \alpha_{en}(i).\sin\alpha_{en}(i) \quad (5)$$

where $\hat{F}$ denotes the predicted cutting force, and $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ are constants, which must be identified in advance by cutting experiments as shown in [Otsuka et al. (2001)]. As the Eq.(5) is a nonlinear equation, a trust-region method for nonlinear optimization is adopted to solve the above equation to obtain a profile of the optimized cutting engagement angle, $\alpha_{en}^*(i)\in R(i=1,\ldots,N_k)$ along the tool path trajectory, $o_k(i)\in R^2(i=1,\ldots,N_k)$ for the given desired cutting force level.

3.3 Tool path modification with optimized cutting engagement angle and implementation of the proposed algorithm

Using the proposed algorithm for tool path modification as described earlier, the trajectory of modified semi-finishing path, $o_{k-1}(i)\in R^2(i=1,\ldots,N_k)$ is generated such that the engagement angle is maintained at $\alpha_{en}^*(i)$ along the trajectory of finishing path, $o_k(i)\in R^2(i=1,\ldots,N_k)$.

4 EXPERIMENTAL VALIDATION OF THE PROPOSED APPROACH

4.1 Machining conditions

Machining experiments on a three-axis vertical machining center (GV503 by Mori Seiki) are carried out. Figure 5 shows the geometry of the core workpiece made of hardened steel (SKD61) used in cutting tests. A radius end mill ((Al-Ti)N-coated sintered tungsten carbide, diameter:10mm, 6 flutes) is used as the cutting tool during down cutting with oil mist as a coolant. Machining strategies adopted in experiments are as follows:

Strategy 1:Under a contour parallel path with constant feedrate at tool center, spindle speed: 4772 min^{-1}, feedrate at the tool center: 1200 mm/min

Strategy 2: Under a feedrate control (to keep constant feedrate at the cutting point), spindle speed: 4772 min^{-1}, feedrate at the cutting point: 1200 mm/min, variable feedrate at the tool center: 450 ~ 2400 mm/min

Strategy 3: Under a feedrate control (same as Strategy 2) and modified tool path (**the proposed approach**), spindle speed: 4772 min^{-1}, feedrate at the cutting point: 1200 mm/min, variable feedrate at tool center: 450 ~ 2400 mm/min

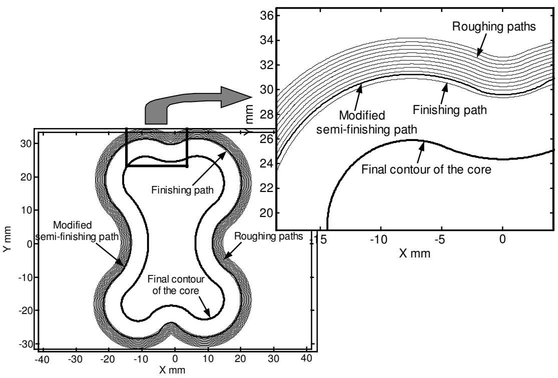


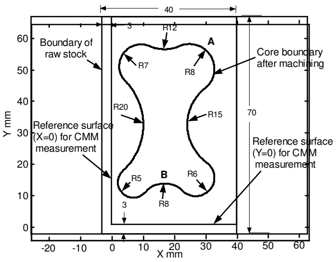
Figure 4. Modified semi-finishing tool path generated by the proposed algorithm on a core contour

Figure 4 shows the modified semi-finishing path generated by the current proposed algorithm, along with the finishing path on a core workpiece. The effect of path modification with optimized cutting engagement angles on the trajectory of semi-finishing tool path can be noticed in the magnified view of tool paths in Fig. 4. Only the semi-finishing path is modified; all other paths are the same as original contour-parallel paths.

During the cutting tests with the above three strategies, axial depth of cut of 5.24 mm and step-over distance of 0.3 mm, are maintained throughout. Note that under Strategy 3, an original contour path with variable feedrate at tool center is applied to finishing (same as Strategy 2) while the modified tool path with a constant feedrate of 1200 mm/min at tool center is applied to semi-finishing.

4.2 Results & discussion

A comparison of cutting forces shown in Fig. 6, measured on the finishing path by using a dynamometer, reveals that machining under a feedrate control with modified tool path (Strategy 3) reduces variation of cutting force by about 80.4% and 44% (max.) compared to those under contour parallel path and feedrate control respectively. In addition, Strategy 3 improves cutting time by about 13% with respect to that under contour parallel path (Strategy 1).



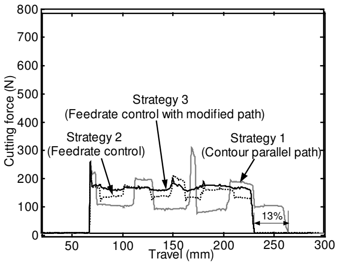
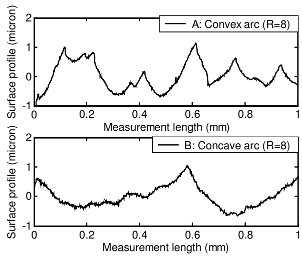
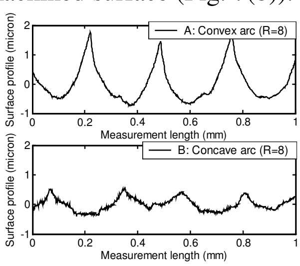


Figure 5. Core workpiece **Figure 6. Cutting force profile**

Surface profiles of machined workpiece measured by a contour form measurement system shown in Fig. 7 indicate that contour parallel path with a constant feedrate generates uneven cutting marks on the surface (Fig. 7(a)) while feedrate control with modified tool path reveals uniform cutting marks on both convex and concave arcs of the machined surface (Fig. 7(b)).



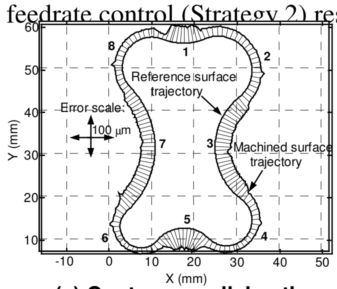
(a) Contour parallel path



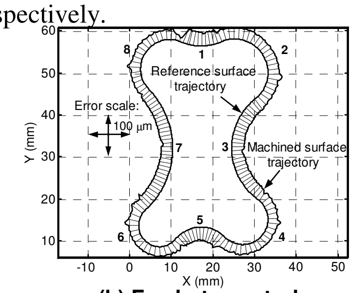
(b) Feedrate control with modified path

Figure 7. Machined surface profiles of convex ('A') and concave ('B') arcs as indicated in Fig. 5

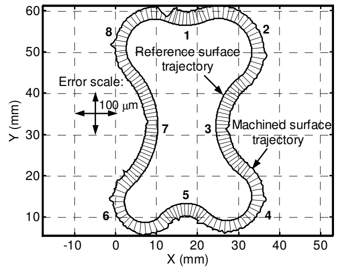
Machined surface trajectories of the core measured by a CMM are shown in Fig. 8. Figure 9 describes the same machined surface error profiles with distance along reference surface in finishing. The numbers on top of graphs in Fig. 9 correspond to those of corner name as shown in Fig. 8. From both figures, it is seen that, in the machining under feedrate control with modified tool path (Strategy 3), machined surface error is more constant along the reference surface trajectory compared to those under other strategies. Neglecting larger error at the entry/exit point of cutting near the point "**1**", the proposed approach (Strategy 3) reduces maximum machined surface error variation by about 57.5% and 19.32% compared to those under conventional contour parallel path (Strategy 1) and feedrate control (Strategy 2) respectively.



(a) Contour parallel path



(b) Feedrate control



(c) Feedrate control with modified path

Figure 8. Machined surface trajectories of the core

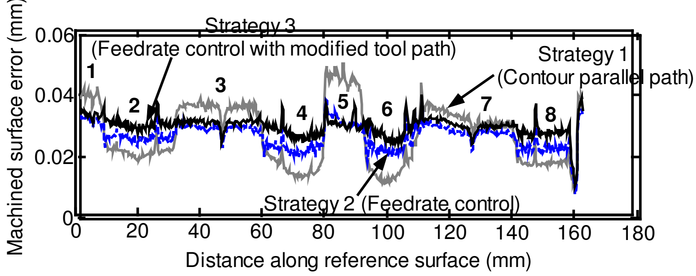


Figure 9. Machined surface error profiles with distance along reference surface of core

5 CONCLUSION

In this paper, an algorithm to generate a new offset tool path, which regulates cutting engagement angle at a desired value, is proposed. An application of the proposed algorithm is demonstrated to a feedrate optimization scheme where feedrate at tool center is varied to keep constant feedrate at cutting point. Results from experimental verification of the proposed approach, include far reduced variation of cutting forces, uniform cutting marks on the machined surface, and an improved geometric accuracy of the machined contour.

REFERENCES

Fussel, B.K., Jerard, R.B. and Hemmet, J.G., 2001, "Robust Feedrate Selection for 3-axis NC Machining Using Discrete Models," *ASME J. of Manuf. Sc. and Eng.*, Vol.123, pp. 214-224

Iwabe, H., Fuji, Y., Saito, K. and Kishinami, T., 1989, "Study on Corner Cut by End Mill Analysis of Cutting Mechanism and New Cutting Method at Inside Corner," *J. of Japan Soc. of Prec. Eng.*, Vol.99 (5), pp. 841-846

Stori, J.A. and Wright, P.K., 2000, "Constant Engagement Tool Path Generation for Convex Geometries," *J. of Manuf. Sys.*, 19(3), pp.172-184

Otsuka, H., Kakino A., Matsubara, A., Nakagawa, H., Hirogaki, T., 2001, "A Study on Endmilling of Hardened Steel (2nd Report)--Control for Constant Cutting Forces in Corner Profile Endmilling including Connection Areas of Tool Paths," *J. of the Japan Soc. of Prec. Eng.*, Vol.67 (8), pp. 1294-1298