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THE IMPROVEMENT OF PRODUCTIVITY AND QUALITY OF DIE/MOLD BY CONSTANT FEEDRATE CONTROL AT THE CUTTING POINT

Susumu Nishida[1], Hirotoshi Ohtsuka[2],
Iwao Yamaji[3], Yoshiaki Kakino[3], Soichi Ibaraki[3], and Atsushi Matsubara[3]
[1] Manufacturing Technology Institute, Inc.
[2] Oita Industrial Research Institute
[3] Department of Precision Engineering, Graduate School of Engineering
Kyoto University

[1]Address : Makuhari Techno Garden B-21, 1-3 Nakase,
Mihama-ku, Chiba 261-8501 Japan.
Tel : +81-43-213-3483, Fax : +81-43-213-3403
E-mail : nishida@mtii.jp

1 Introduction

In the machining of dies and molds, where contour parallel offset tool paths are often used, the feedrate in NC programs is defined mostly as the velocity at a cutter center, since it is easier to compute. In the machining of a convex arc, the feedrate at actual cutting point can be a couple of times larger than the case where the same feedrate is applied to a straight path. On the other hand, in the machining of a concave arc, it can be a couple of times smaller than the case of straight cutting. The variation of feedrate at the cutting point results in the variation of the feed per tooth, which causes the variation of cutting forces. It causes the variation of tool deflection, and the deterioration of the machining accuracy and the surface finish.

To address this issue, we have developed an NC program generation system that regulates the feedrate at the cutting point at a constant level. Its effectiveness is verified through machining tests on hardened steel.

2 Definition of the Feedrate at Cutting Point and Its Regulation

Figure 1 depicts the definition of the feedrate at the cutting point, as well as the conventional definition of the feedrate at the cutter center. In the machining of free-form contours, as commonly seen in die and mold machining, it can be easily observed that the feed per tooth may significantly vary even when the feedrate at the cutter center is constant. In order to regulate the feed per tooth constant, the feedrate at the cutter center must be changed according to the path geometry.

In order to keep the feedrate at the cutting point at the given desired value, the feedrate at the cutter center must be computed as follows. First, a series of minute line segments consisting of a tool path is approximated by a polynomial curve. Then, the curvature radius and the curvature center are computed at each interpolation point (See Fig. 2).

To regulate the feedrate at cutting point at the given level, namely F_p, the feedrate at the cutter center, $F_c(i)$, is given by:

$$F_c(i) = \frac{R_i \cdot F_p}{|P_i O_i|} \quad (1)$$

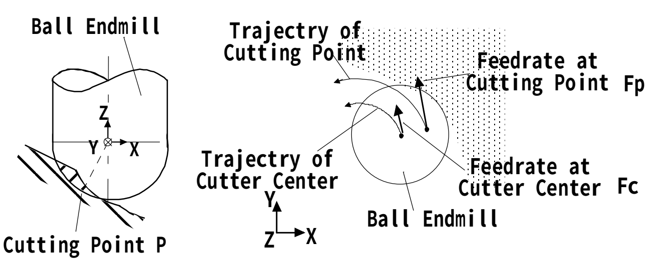


Figure 1 The definitions of Feedrate at Cutter Center and at Cutting Point

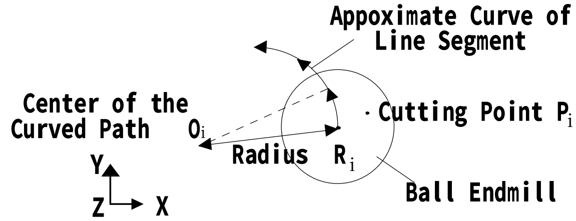


Figure 2 The curvature radius and the curvature center for an approximate curve of tool path segments

As an example, the feedrate at the cutter center is optimized by using Eq. (1) on finishing tool paths for a battery charger mold for a cellular phone shown in Fig.3. A part of the optimized feedrate profile is shown in Fig. 4. As can be observed from the figure, on the "outer" arc path to machine a convex surface (Point A), the feedrate at cutter center is regulated to be 3.2 times larger at maximum than that on a straight path. On the other hand, on the "inner" arc path to machine a concave surface (Point B), the feedrate is decreased to 61 % of that in a straight path at maximum.

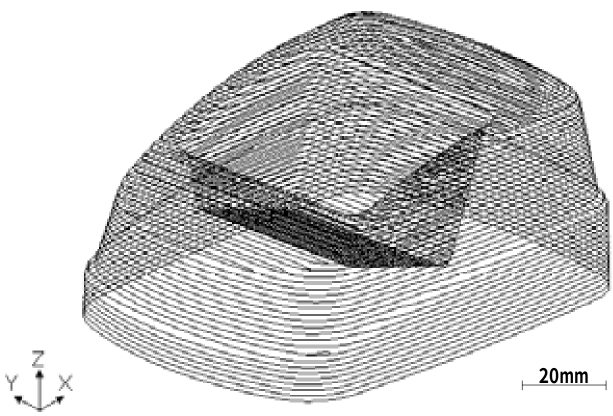
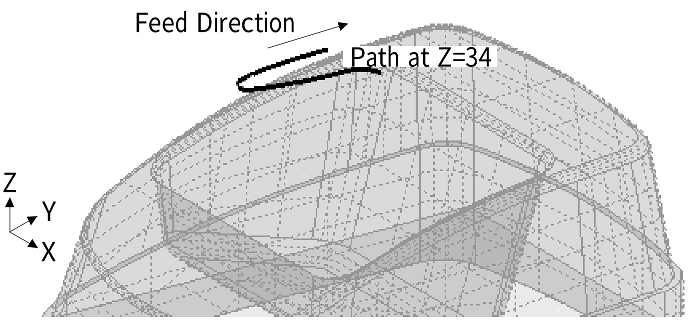
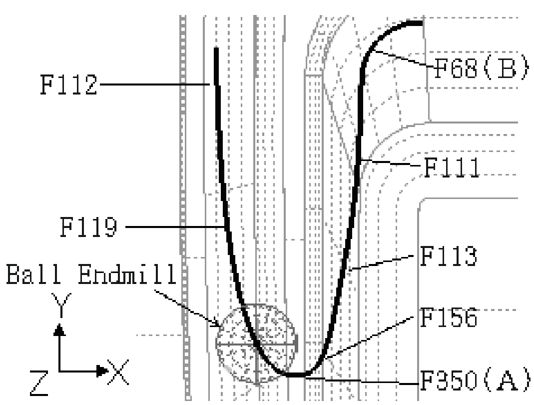


Figure 3 Finishing tool paths for a battery charger mold for a cellular phone



(a) Bird view



(b) Top view

Figure 4 The optimized profile of the feedrate at cutter center (excerption)

3 Machining Experiment

3.1 Machining Conditions

Since it is difficult to evaluate the machining accuracy on the battery charger mold shown in Fig. 3, we conducted machining experiments on a mold of a simpler wave-form geometry shown in Fig. 5. Machining conditions are as follows:

Workpiece: die steel, SKD61(HRC53)

Tool: (Al, Ti)N-coated sintered carbide ball end mill (ball radius: 3mm, 2 flutes)

Machining test #1: conventional strategy (under a constant feedrate at the cutter center)
Spindle speed: 8,000 min^{-1}
Feedrate at cutter center: 1200 mm/min (feed per tooth: 75 μ m/tooth)

Machining test #2: under a constant feedrate at the cutting point
Spindle speed: 8,000 min^{-1}
Feedrate at cutting point: 1200 mm/min (feed per tooth: 75 μ m /tooth)

Machining test #3: under a constant feedrate at the cutting point, with the maximum changing rate of feedrate restricted
Spindle speed: 8,000 min^{-1}
Feedrate at cutting point: 1000 ~ 1400 mm/min (feed per tooth: 63 ~ 88 μ m/tooth)

In the machining test #2, there are regions where the feedrate at the cutter center is abruptly changed in order to strictly regulate the feedrate at the cutting point. In the machining test #3, the maximum changing rate of the feedrate at the cutter center is restricted to some threshold, and thus the feedrate is changed at a slower rate. The machining tests #1, #2, and #3 were conducted by using tool paths and feedrates shown in Figs. 6(a), 6(b), and 6(c), respectively.

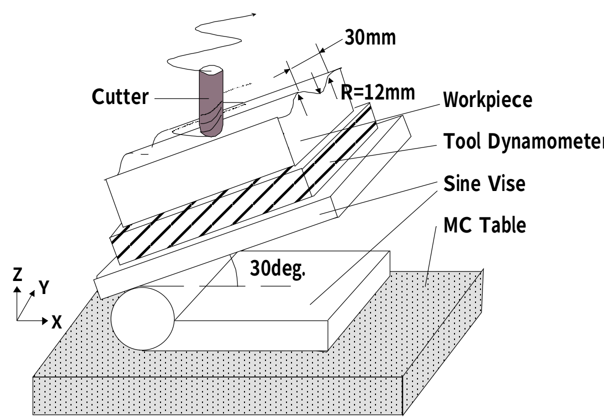


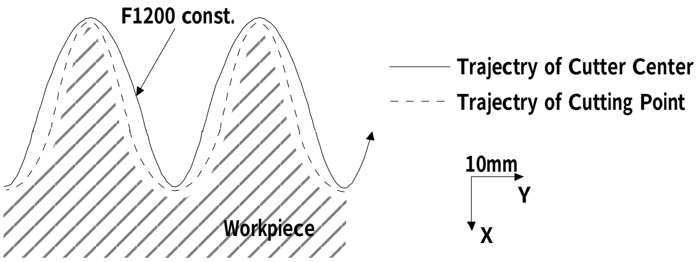
Figure 5 Schematics of machining test

3.2 Experimental Results and Discussion

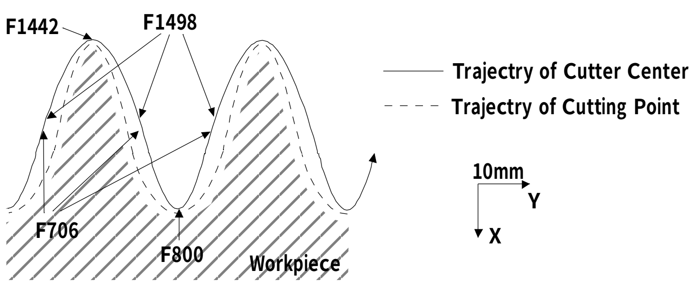
Figure 7 shows the comparison of the measured cutting forces between two cases. It can be observed that the variation of cutting forces is smaller under a constant feedrate at the cutting point. Note that the machining time is defined as the time to machine from ① to ③ in Fig. 8.

Surface profiles under both cases are compared in Figs. 9 and 10. As shown in Fig. 9(b), the distance between each cutter mark is larger in the valley than that in a peak, and the surface roughness is also larger in a valley, when the feedrate at the cutter center is constant.. On the other hand, when the feedrate at the cutting point is regulated constant, cutter marks look the same in a valley and in a peak as shown in Fig. 10(b). This improves the smaller surface roughness under a constant feedrate at the cutting point.

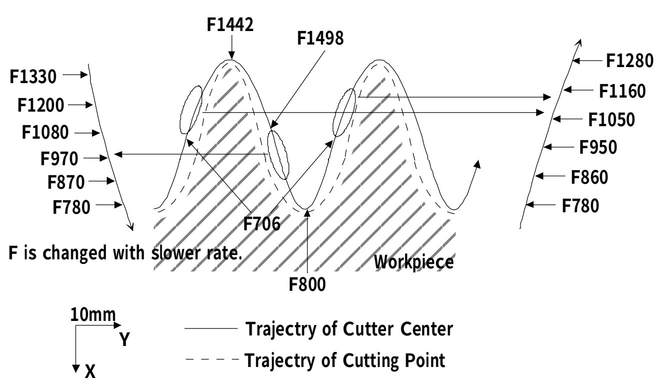
The surface roughness under the restriction of the maximum changing rate of feedrate (Machining test #3) was about the same as the case without the restriction (Machining test #2).



(a) Machining test #1: under a constant feedrate at cutter center



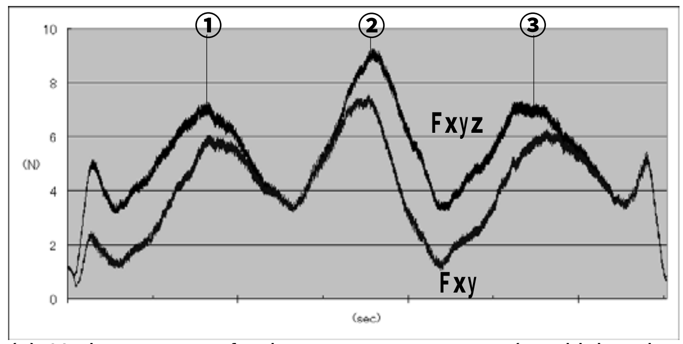
(b) Machining test #2: under a constant feedrate at cutting point



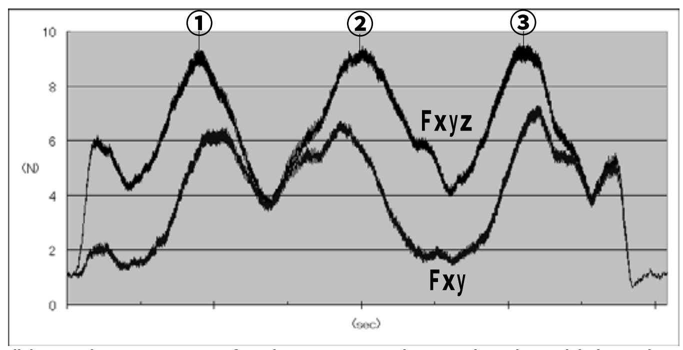
(c) Machining test #3: under a constant feedrate at cutting point with the maximum changing rate of feedrate restricted

Figure 6 Tool paths and feedrate

Table 1 summarizes experimental results. The difference between maximum and minimum cutting forces is smaller under a constant feedrate at the cutting point, which reduces the effect of the tool deflection on the surface roughness. The cutting force at the middle of a valley and a peak is smaller than that in a valley or in a peak, since the tool rotation radius is larger there. To further clarify this, the relation between the cutting point location on a ball end mill and the cutting force is shown in Fig. 11. The maximum height of surface roughness is also smaller under a constant feedrate at the tool center. If the maximum height of surface roughness is the same as that under a constant feedrate at tool center, the machining time becomes about 1.59 sec by the following equation. That is, the machining time can be shortened by applying a constant feedrate at the cutting point.



(a) Under constant feedrate at cutter center (machining time: 1.89 sec)



(b) Under constant feedrate at cutting point (machining time: 2.19 sec)

Figure 7 Comparison of measured cutting forces

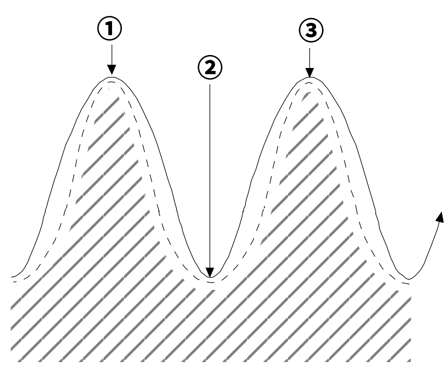
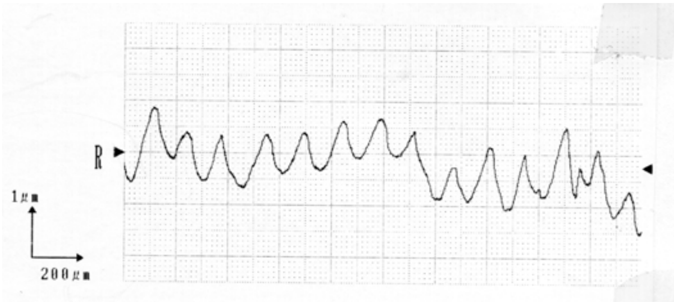


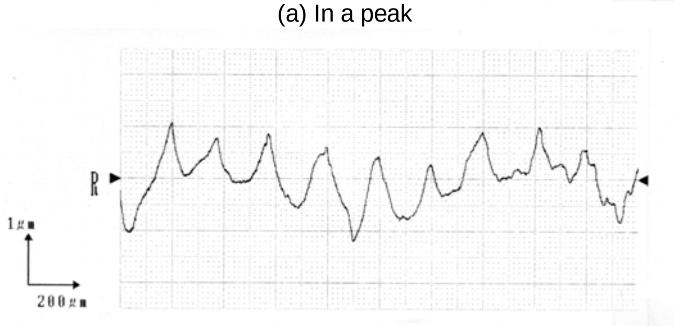
Figure 8 Machining Location

$$2.19 \times 0.8 \div 1.1 = 1.59 \quad (2)$$

Since the surface at the middle part is slanted, the surface roughness there could not be measured. By the visual check, the surface roughness seemed approximately the same in both cases.

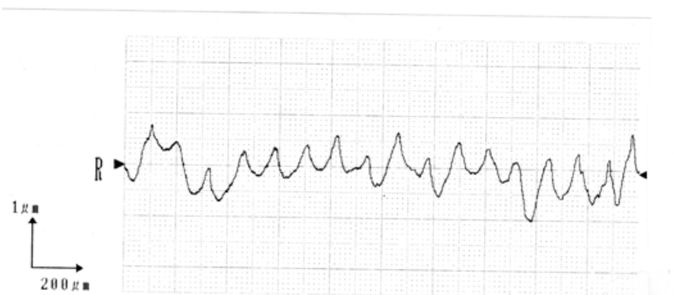


(a) In a peak

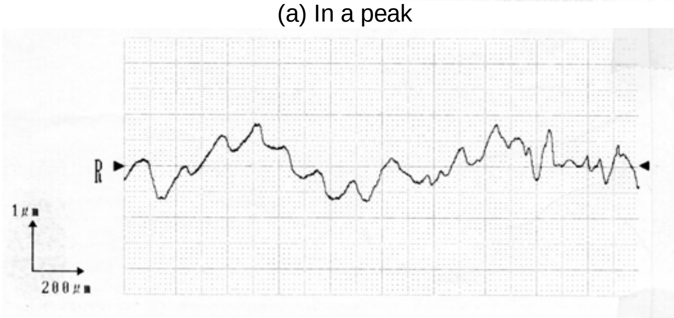


(b) In a valley

Figure 9 Surface profiles under a constant feedrate at the cutter center



(a) In a peak



(b) In a valley

Figure 10 Surface profiles under a constant feedrate at the cutting point

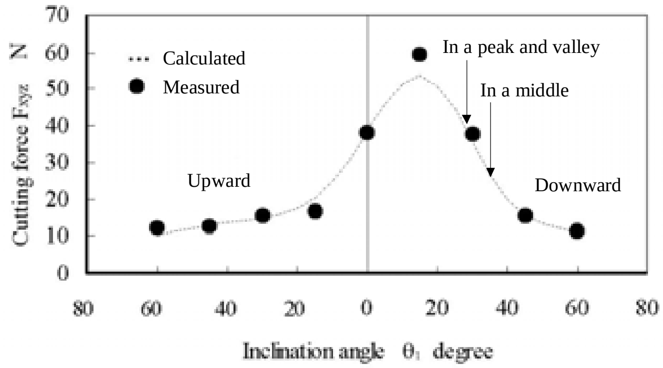


Figure 11 Relationship between the cutting point location on a ball end mill and the cutting force

Table 1 Comparison of cutting force, surface roughness, and machining time under a constant feedrate at the cutter center and a constant feedrate at the cutting point

Effect	Location	constant feedrate at cutter center		constant feedrate at cutting point	
Cutting force (F_{xy})	Peak ① ③	6.0 N	Difference ≈ 6.0 N	7.2 N	Difference ≈ 5.4 N
	Middle	1.3 N		1.8 N	
	Valley ②	7.3 N		6.2 N	
Surface roughness	Peak ① ③	0.5 μm	Maximum ≈ 1.1 μm	0.8 μm	Maximum ≈ 0.8 μm
	Middle	—		—	
	Valley ②	1.1 μm		0.6 μm	
Machining time under the assumption of constant surface roughness		1.89sec（100%）		1.59sec（84%）	

4 Conclusion

In a finishing process by a ball end mill, the machining under a constant feedrate at the cutting point was compared with the conventional manner under a constant feedrate at the cutter center. The following conclusions were drawn:

1) The variation of surface finish became smaller under a constant feedrate at the cutting point than that under a constant feedrate at the cutter center.
2) In order to achieve the same surface finish, the machining time under a constant feedrate at the cutting point became shorter than that under a constant feedrate at the cutter center. This is also the case for more general mold geometries.
3) Under a constant feedrate at the cutting point, the variation of cutting forces, F_{xyz} and F_{xy}, became smaller than the case under a constant feedrate at the cutter center, which reduced the effect of the tool deflection on the machining accuracy. However, since there still remain the regions subject to too small cutting forces, the variation of cutting forces cannot be completely diminished even when a constant feedrate at the tool center is applied.