A CONSTANT CUTTING FORCE CONTROL FOR FINISHING PROCESS OF DIE AND MOLD BY USING A BALL END MILL

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Abstract In a finishing process of die and mold by using a ball end mill, a contour parallel tool path is usually used under a constant depth of cut (typically around 0.1 mm) and a constant feedrate. In such a process, the cutting force acting on a tool is usually less than 20 N. It varies, however, significantly along the tool path, which naturally causes the variation of tool deflection, and then deteriorates the machining accuracy. To address this issue, we propose a tool path modification scheme to control the depth of cut in an intermediate-finishing process, such that the cutting force is regulated constant in a finishing process and thus the machining accuracy is improved. To this goal, in this paper we experimentally investigate the following:

1) the relationship between the angular location of the cutting point on a tool and the cutting force, and
2) the relationship between the depth of cut and the cutting force.

The relationship between the depth of cut and the engagement angle can be computed from a CAD model. A mathematical prediction model of cutting forces can be identified based on these relationships.

Keywords: finishing process ,ball end mill, cutting force, machining accuracy, cutting point, engagement angle

1. INTRODUCTION

In a finishing process of die and mold by using a ball end mill, a contour parallel tool path is usually used under a constant depth of cut (typically about 0.1 mm) and a constant feedrate. In such a process, the cutting force acting on a tool is usually less than 20 N. However, it significantly varies depending on the machining geometry, which causes the variation of tool deflection, and then deteriorates the machining accuracy.

To address this issue, we propose a tool path design scheme to control the depth of cut in an intermediate-finishing process, such that the cutting force in a finishing process is regulated constant and thus the machining accuracy is improved. To this goal, this paper presents the experimental investigation on:

1) the distribution of cutting force along a cutting edge, and
2) the relationship between the depth of cut and the cutting force.

Based on the relationship between the depth of cut and the engagement angle, which can be computed from a CAD model, a mathematical model to predict the cutting force is established. Otsuka et al.[1)] proposed a mathematical model to estimate the cutting force for a ball end mill. Since this model has nine parameters to be identified, it is too complex to be applied to the machining by a ball end mill, which requires more complex computation. This paper proposed a simpler model for cutting force estimation.

By using the proposed model, an NC program for an intermediate-finishing process is designed such that it generates the stock geometry that makes the cutting force on a finishing path constant. The effectiveness of the proposed scheme is validated by experimental tests to machine a mold of hardened steel.

2. A MATHEMATICAL MODEL OF CUTTING FORCE

For the estimation of the cutting force, this paper employs a model of two variables given in Eq. (1). As shown in Fig. 1, a ball-shaped cutting edge is divided in the z-direction, and the cutting force ΔF acting on each layer is accumulated to estimate the overall cutting force, F. Two parameters, the undeformed chip thickness t_m and the arc length of cutting engagement, L, are computed as a function of Z from the machining geometry at each layer.

The cutting force ΔF_{xy} generated in the machining of a thin layer of the depth ΔZ is modeled as:

$$\Delta F_{xy} = (C_0+C_1*L+C_2*t_m+C_3*L*t_m)*\Delta Z \qquad (1)$$

This is a simplified version of the model proposed by Otsuka et al. Their model consists of the terms with t_m, t_m^2, L, L^2, and t_m*L, while the model (1) only includes the terms with t_m, L, and t_m*L.

The overall cutting force is given as the integration of the layer-to-layer cutting force given above over an entire cutting edge:

$$F_{xy} = \sum_{Z} (C_0+C_1*L(z)+C_2*t_m(z)+C_3*L(z)*t_m(z))*\Delta Z \qquad (2)$$

In practice, the layer-to-layer cutting force acting on a cutting edge is measured as follows: first, the cutting force is measured under the given axial depth of cut. Then, increase the axial depth of cut by ΔZ, and then measure the cutting force. The difference in the measured cutting force is considered as the cutting force acting on this layer. By repeating this, the distribution of cutting force can be measured over the entire cutting edge.

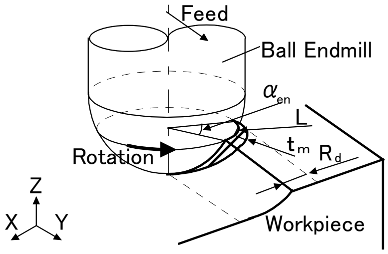


Figure 1: A cutting model of a ball end mill

3. EXPERIMENTAL SETUP AND PROCEDURE FOR MODEL IDENTIFICATION

An overview of the experimental setup is illustrated in Fig. 2. A flat-plate workpiece is installed on a table of a machining center with a dynamometer. Its top surface is machined by pick-feed cutting with the cutting force measured. The same machining tests are repeated with changing the depth of cut in the z-direction by one-tenth of the ball radius.

First, as shown in Fig. 3(a), the cutting force is measured when the axial depth of cut in the z-direction is one-tenth of the ball radius. Then, as shown in Fig. 3(b), the same machining toward the horizontal direction is repeated with the axial depth of cut of two-tenth of the ball radius. Similarly, the axial depth of cut is increased by one-tenth of the ball radius and the same machining test is repeated.

The machining center, the tool, the workpiece, and machining conditions used in the experiments are as follows:

Machining center: A machining center, YBM950V, by Yasuda Precision Tools, K. K.
Tool: An (Al, Ti)N-coated sintered carbide ball end mill (diameter: 6mm, 2 flutes)
Tool extension: 30mm
Workpiece: die steel, SKD61 (HRC53)
Machining conditions:
  Spindle speed: 9600 min^{-1}
  Feedrate: 0.05 mm/tooth (960 mm/min)

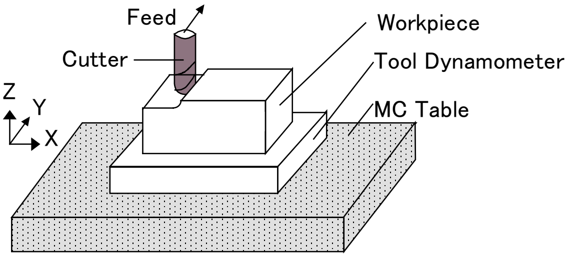
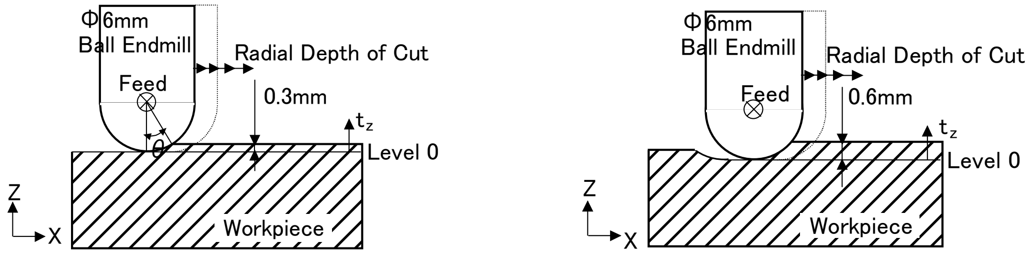


Figure 2: Experimental setup



(a) the axial depth of cut: 1/10 of the ball radius (b) the axial depth of cut: 2/10 of the ball radius

Figure 3: The depth of cut in each machining test

4. EXPERIMENTAL RESULTS AND INTERPRETATION

The distribution of cutting force along a ball cutting edge measured as described in the previous section is shown in Fig. 4. The layer-to-layer cutting force becomes larger in lower layers. As the tool tip engagement angle becomes larger, it decreases monotonously. It is because the relative cutting force is larger when the tool tip engagement angle is smaller, due to the dimensional effect on the cutting force, since the actual depth of cut is smaller near the tool tip.

The coefficients, C_i, in Eq. (1) can be identified by using the second-order response surface model based on the measured cutting force in the XY plane, F_{xy}. The chip thickness, t_m, and the arc length of cutting engagement, L, can be calculated from a CAD model. The range of t_m and L is determined as the maximum and minimum values of t_m and L in the experiments.

The measurement points on the response surface are summarized in Table 1. The coefficient of determination adjusted for the degrees of freedom is 0.94, which indicates that the approximation is in a sufficient accuracy.

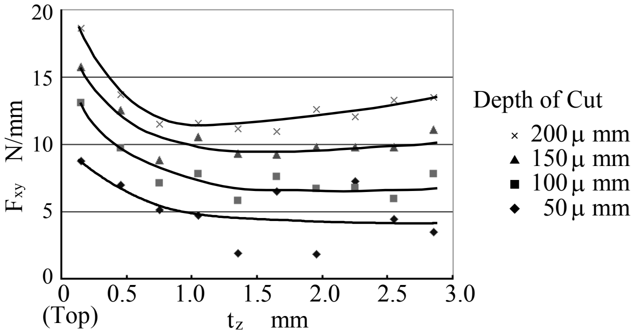


Figure 4: The distribution of cutting force along a cutting edge

Table 1: Measurement points on the response surface

No.	tz (mm)	R_d(μm)	f (mm/min)	t_m(μm)	L (μm)	F_{xy} (N)	X_1 (t_m)	X_2 (L)
1	2.85	150	960	15	952	3.32	0.2	0.545
2	2.85	200	960	18	1101	4.05	0.6	1
3	1.65	50	960	9	518	2.19	-0.6	-0.78
4	1.65	100	960	13	734	2.55	-0.067	-0.121
5	0.75	50	960	11	446	2.34	-0.333	-1
6	0.75	200	960	21	899	5.25	1	0.383
7	2.85	100	480	6	776	2.13	-1	0.008
8	1.65	100	480	7	734	2	-0.867	-0.121
9	1.65	100	960	13	734	2.47	-0.067	-0.121
10	0.75	100	1200	19	633	4.06	0.733	-0.429

5. CASE STUDIES

In this section, we present case studies of a finishing process of a mold. By comparing two methods for tool path planning, the validity of the mathematical model of cutting force presented in the previous sections is investigated.

5.1 Mold geometries

To investigate the validity of the cutting force estimation model, the following two molds are machined as case studies. The cutting force is measured to compare with its estimate.

1) A mold of a quarter-cylinder geometry

A mold of a quarter-cylinder geometry shown in Fig. 5 is machined by using direction-parallel tool paths in the horizontal direction. The cutting force, F_{xy}, is compared under the following two conditions: 1) the step-over is constant throughout, and 2) the step-over is optimized by using the proposed scheme.

2) A tapered petal-shaped mold

A mold of a tapered petal-like geometry shown in Fig. 7 is machined by using horizontal contour-parallel tool paths. The cutting force, F_{xy}, is compared under conventional and proposed tool path design schemes.

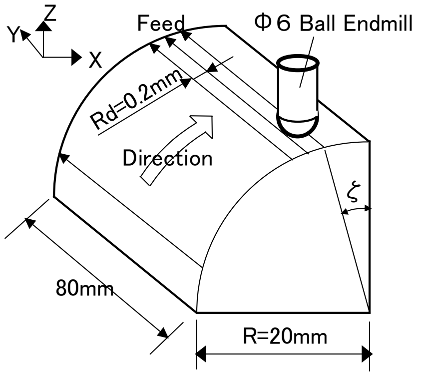


Figure 5: A mold of a quarter-cylinder geometry

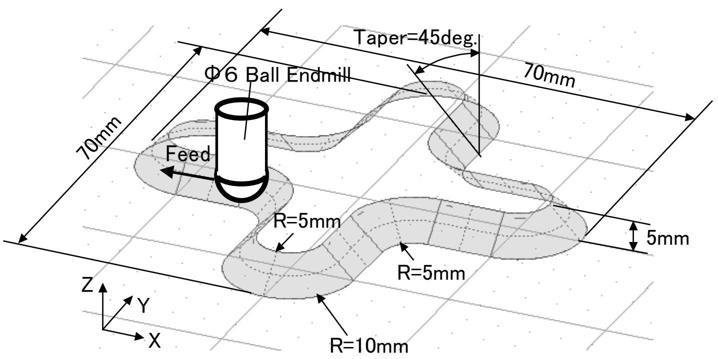
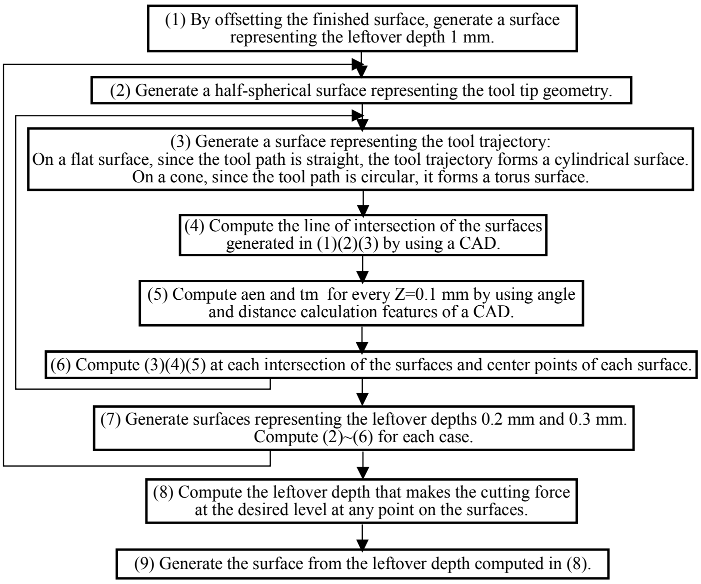


Figure 6: A tapered petal-shaped mold

5.2 The computation of the semi-finished geometry to regulate the cutting force in the finishing

We propose a tool path generation scheme for a semi-finishing such that it generate the stock geometry (=semi-finishing geometry) that makes the cutting force in the finishing constant. The algorithm is outlined as shown in Fig. 7.



(1) By offsetting the finished surface, generate a surface representing the leftover depth 1 mm.

(2) Generate a half-spherical surface representing the tool tip geometry.

(3) Generate a surface representing the tool trajectory:
On a flat surface, since the tool path is straight, the tool trajectory forms a cylindrical surface.
On a cone, since the tool path is circular, it forms a torus surface.

(4) Compute the line of intersection of the surfaces generated in (1)(2)(3) by using a CAD.

(5) Compute aen and tm for every Z=0.1 mm by using angle and distance calculation features of a CAD.

(6) Compute (3)(4)(5) at each intersection of the surfaces and center points of each surface.

(7) Generate surfaces representing the leftover depths 0.2 mm and 0.3 mm. Compute (2)~(6) for each case.

(8) Compute the leftover depth that makes the cutting force at the desired level at any point on the surfaces.

(9) Generate the surface from the leftover depth computed in (8).

Figure 7: An algorithm to generate a tool path for constant cutting force

5.3 Experimental setup and procedure

The experimental setup and cutting conditions are the same as those in the previous experiments for the model identification.

Tool: An (Al, Ti)N-coated sintered carbide ball end mill (diameter: 6mm, 2 flutes)
Workpiece: die steel, SKD61 (HRC53)
Machining conditions:
Spindle speed: 9600 min^{-1}
Feedrate: 0.05 mm/tooth (960 mm/min)

5.4 Experimental results and interpretation

In the case of the quarter cylindrical mold, Fig. 8 presents the comparison of the cutting force between the case where the depth of cut is constant at 0.1 mm, and the case where the depth of cut is varied such that the cutting force, F_{xy}, is regulated constant at 10 N by applying the algorithm shown in Fig. 7. In the latter case, the cutting force, F_{xy}, is approximately constant in the range of the angle 5°~75°.

In the case of the tapered petal-shaped mold, Fig. 9(a) shows the cutting force measured through the machining when the depth of cut is constant at 0.2 mm. Figure 9(b) shows the case where the depth of cut is varied within 0.12~0.22 mm. In the constant depth of cut case, the cutting force, F_{xy}, varied within 4~18 N, while its variation was much smaller (5~10N) when the depth of cut is controlled. In Fig. 9(a), the cutting force, F_{xy}, increases at a convex corner. On a concave corner, the cutting force, F_{xy}, is supposed to decrease. In experimental results, however, only the increase of the vibration was observed, and no significant decrease of the cutting force, F_{xy}, was observed.

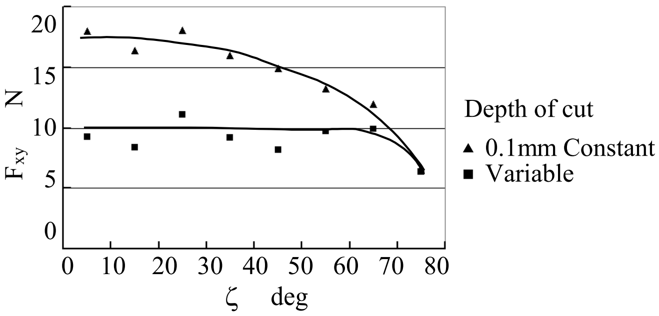
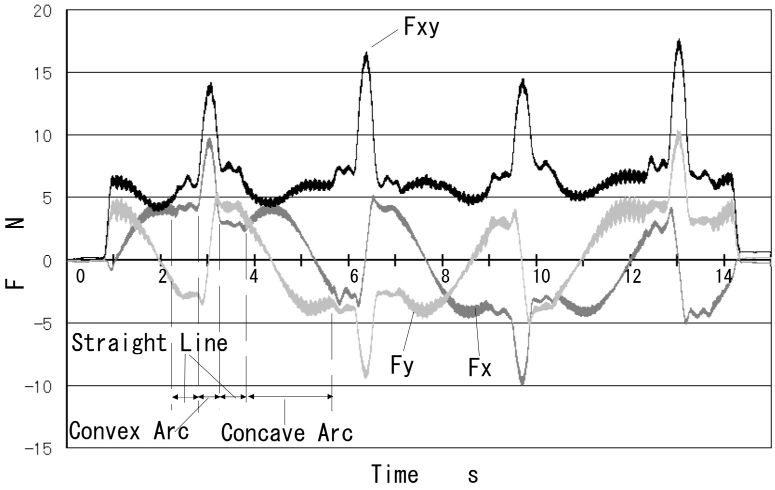
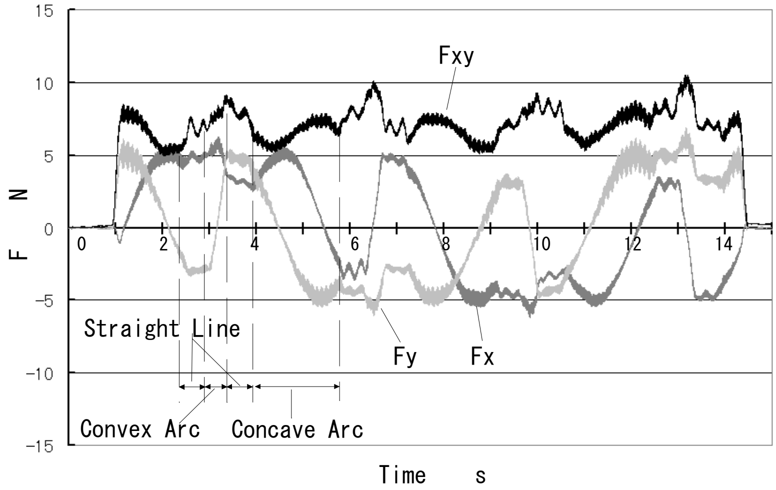


Figure 8: Comparison of cutting force in the machining of the quarter cylindrical mold



(a) Under a constant depth of cut



(b) Under the variable depth of cut

Figure 9: Cutting forces in the machining of the tapered petal-shaped mold

6. CONCLUSIONS

In this paper, we studied a cutting force control in die and mold machining by a ball end mill. The conclusions of this paper are summarized as follows:

1. In a finishing process of a mold by using a ball end mill, the distribution of cutting force along a cutting edge was measured. Based on it, a simple mathematical model was proposed to estimate the overall cutting force.
2. A scheme to compute the variation of the radial depth of cut in a finishing process by using the mathematical model above was developed.
3. By regulating the radial depth of cut in a finishing process by using the proposed scheme, the cutting force was regulated constant.

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