DEVELOPMENT OF A VIRTUAL MACHINING SYSTEM FOR ESTIMATION OF CUTTING PERFORMANCE

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ABSTRACT

Present CAM technology cannot provide important physical property such as cutting force and machined surface. Thus, the selection of cutting conditions still depends on the experience of an expert or on the machining data handbook in spite of the developed CAM technology. This paper presents an advanced methodology to help the worker to determine optimum cutting condition for CNC machining that excludes the need for expertise or machining data handbook. The virtual machining system presented in this paper can simulate the real machining states such as cutting force and machined surface error. And virtual machining system can schedule feed rate to adjust the cutting force to the reference force.

1 INTRODUCTION

The ability to automatically generate an optimum process plan is an essential step toward achieving automation, higher productivity, and better accuracy in CNC machining. This requirement is particularly emphasized in die and mold manufacturing, where complex tool and workpiece geometry involved makes it difficult to generate the process plan. However, the need for the process planning becomes more demanding due to high cost in die production, narrow tolerance requirements, and the continuous demand for new components. Thus, the current research trend in this theme is to develop a system that is capable of simulating the actual machining process, rather than simple geometric design [1].

Present CAM technology cannot provide the important physical properties such as the cutting forces and the machined surfaces. Thus, the selection of cutting conditions still depends on the experience of a machinist or on a machining data handbook in spite of the developed CAM technology [2].

This paper presents a virtual machining system to evaluate cutting performance for CNC machining. The virtual machining system developed in this paper has the cutting process module including mechanistic cutting force model and machined surface error model. It is shown that cutting forces and the machined surface errors predicted by the cutting process module are in good agreement with the measured ones in both shape and magnitude. Also off-line feed rate scheduling based on the cutting process simulation is presented.

2 PHYSICAL MODELS FOR ESTIMATION OF CUTTING PERFORMANCE

2.1 Mechanistic Cutting Force Model

The end milling cutter can be divided into a finite number of disk elements and the total x-, y-, and z-force components acting on a flute at a particular instant are obtained by numerically integrating the force components acting on an individual disk element. Finally, a summation over all flutes engaged in cutting yields the total forces acting on the cutter at that time. Figure 1 shows schematic views of an end milling process geometry and coordinate system. The cross section of the cutter geometry is shown in Figure 2.

The angular position (ϕ) of the k-th axial disk element of the i-th flute at the j-th angular position ($\theta(j)$) of the cutter is given by Equations (1) and (2):

$$\phi(i,j,k) = \theta(j) + (i-1)\phi_c + (k\Delta a + \Delta a/2)\frac{\tan\theta_h}{R} \quad (1)$$

$$\theta(j) = -j\Delta\theta \quad (2)$$

where θ_h and R are the helix angle and radius of the cutter, respectively; ϕ_c is a flute spacing angle; Δa is height of z-axis disk element; $\Delta\theta$ is cutter rotation angle increment.

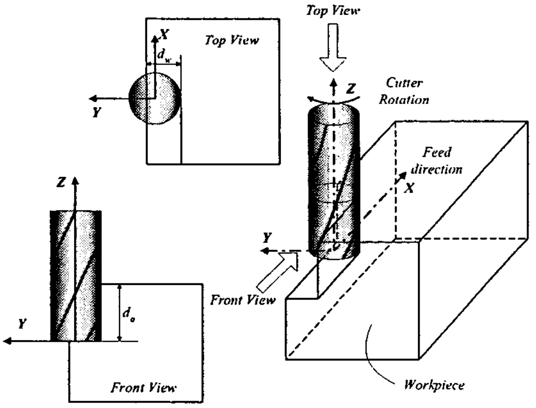


Fig. 1 Schematic views of end milling process geometry and coordinate

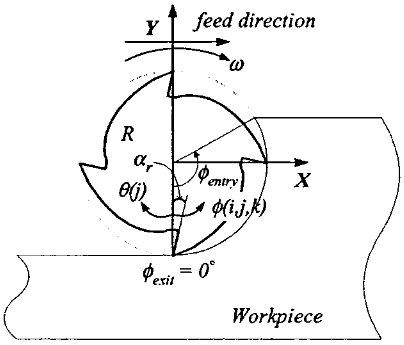


Fig. 2 Cutter rotation angle and cutting edge location angle on a cross section of an end mill cutter

The three orthogonal force components in Cartesian coordinates can be derived as follows:

$$
\begin{aligned}
F_x(j) &= \sum_i \sum_k [C_1 K_n \cos(\phi - \alpha_r) + K_f K_n C_3 \cos\phi \\
&\qquad - K_f K_n C_4 \sin(\phi - \alpha_r)] t_c(\phi) B_1 \\
F_y(j) &= \sum_i \sum_k [C_1 K_n \sin(\phi - \alpha_r) + K_f K_n C_3 \sin\phi \\
&\qquad + K_f K_n C_4 \cos(\phi - \alpha_r)] t_c(\phi) B_1 \\
F_z(j) &= \sum_i \sum_k [-C_2 K_n + K_f K_n C_5] t_c(\phi) B_1
\end{aligned}
\tag{3}
$$

where,

$$C_1 = \cos\theta_h / \sin\theta_{tk}, \quad C_2 = \sin\theta_h / \sin\theta_{tk},$$

$$C_3 = \sin\theta_h (\sin\theta_c - \cos\theta_c \cot\theta_{tk}),$$

$$C_4 = \cos\theta_c / \sin\theta_{tk},$$

$$C_5 = \cos\theta_h (\sin\theta_c - \cos\theta_c \cot\theta_{tk}),$$

$$B_1 = \cos\alpha_r (\Delta a / \cos\theta_h), \quad \cos\theta_{tk} = \sin\alpha_r \cdot \sin\theta_h,$$

α_r : rake angle of the cutter

In Equation (3), the cutting forces can be predicted using the uncut chip thickness ($t_c(\phi)$) and cutting force coefficients including the specific cutting forces (K_n, K_f) and chip flow angle (θ_c) [3].

2.1.1 Uncut chip Thickness Model

In the mechanistic cutting force model, the uncut chip thickness is calculated as a function of the position of the center of the cutter for each *z*-axis disk element. The position of the center of the cutter deviates from its nominal positions due to numerous factors such as cutter deflection, runout, servo error, volumetric error, thermal error, wear, etc. Of all the factors, cutter deflection and runout account for the most deviation. Thus, the actual position of the center of the cutter, (x_a, y_a), can be realistically represented as Equation (4):

$$
\begin{aligned}
x_a(j,k) &= x_n(j) + x_p(j) + x_d(j,k) \\
y_a(j,k) &= y_n(j) + y_p(j) + y_d(j,k)
\end{aligned}
\tag{4}
$$

where (x_n, y_n) is the nominal position of a cutter and (x_p, y_p) and (x_d, y_d) are the deviations caused by cutter runout and deflection, respectively. The uncut chip thickness can therefore be estimated from the position of the center of the cutter [4]. The uncut chip thickness is the distance between the path that the current tooth of interest is generating, and the exposed workpiece surface generated by the previous tooth. The uncut chip thickness model including cutter runout and deflection is used to predict mechanistic cutting force and machined surface errors.

2.1.2 Model Validation

A set of 21 steady state cutting tests were carried out as listed in Table 1. All the tests were conducted with HSS end mills with four flutes, 30° helix angle, 11° rake angle and 10mm diameter, in a vertical type-machining center (Daewoo Heavy Industries Ltd., ACE-V30). A tool dynamometer (Kistler, type 9257B) was used to measure the three components, F_x, F_y and F_z, of the instantaneous cutting forces. The workpiece material was aluminum 2014-T6.

To verify the proposed method, cutting force predictions were made. The cutting coefficients were calculated using the measured cutting forces for Test 17[5][6]. In all the predictions, the values listed in Table 2 were used.

Table 1. Cutting Conditions

No	d_a (mm)	d_w (mm)	f_t (mm/ tooth)	RPM
1	2.0	5.0	0.0375	1000
2	4.0	5.0	0.0375	1000
3	5.0	5.0	0.0375	1000
4	6.0	5.0	0.0375	1000
5	8.0	5.0	0.0375	1000
6	5.0	1.0	0.0375	1000
7	5.0	2.5	0.0375	1000
8	5.0	4.0	0.0375	1000
9	5.0	6.0	0.0375	1000
10	5.0	7.5	0.0375	1000
11	5.0	9.0	0.0375	1000
12	5.0	5.0	0.0250	1000
13	5.0	5.0	0.0300	1000
14	5.0	5.0	0.0350	1000
15	5.0	5.0	0.0400	1000
16	5.0	5.0	0.0450	1000
17	5.0	5.0	0.0500	1000
18	5.0	5.0	0.0375	1000
19	5.0	5.0	0.0375	800
20	5.0	5.0	0.0375	1200
21	5.0	10.0	0.0375	1500

Table 2. Cutting Coefficients

K_f	θ_c (rad.)	ρ (μ m)	α_{run} (deg.)
0.8287	0.471	6	95

$K_n(j)$ was calculated by Equations (5) and (6).

$$t_{cn}(j) = \frac{t_c(j)}{(t_{cg,\max} - t_{cg,\min})} \tag{5}$$

$$\ln(K_n) = \frac{A_1 - A_2}{1 + e^{(t_{cn} - x_0)/dx}} + A_2 \tag{6}$$

The fitted result for $t_{cn}(j)$ and log scaled $K_n(j)$, which were calculated using the measured cutting forces for Test 17 is as follows: A_1 = 12.9122, A_2 = 6.73768, x_0 = -0.62399, dx = 0.44168

The x-, y-, and z- cutting force components were obtained from Equation (3) using these values. Figure 3 shows the predicted and measured cutting forces for Test 3. Figure 4 compares the predicted and measured results for different width of cut (Test 7). From the figures, good agreement can be observed again between the predicted and measured forces in both magnitudes and shapes, regardless of the change in cutting conditions[7].

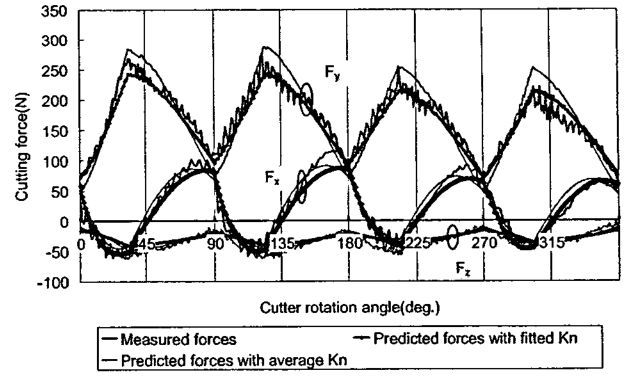


Fig. 3 Comparison of measured and predicted cutting forces for Test 3

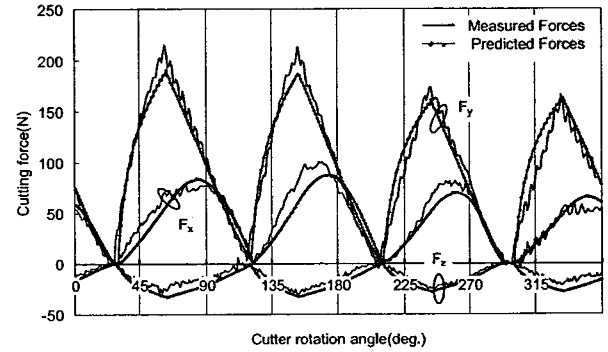


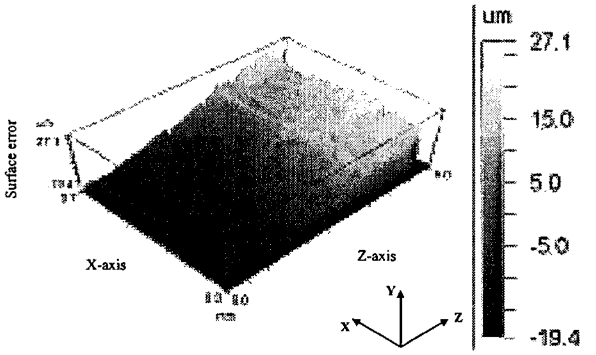
Fig. 4 Comparison of measured and predicted cutting forces for Test 7

2.2 Machined Surface Error Model

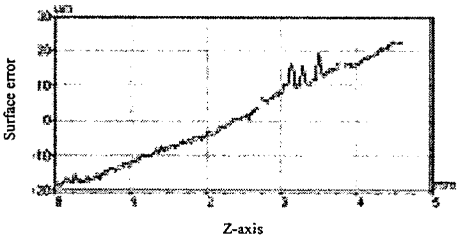
Most of the existing models predict the two-dimensional surface error in the direction of the axial depth of the workpiece under fixed cutting conditions. However, these models cannot be applied to general cutting processes such as transient cuts and pocket machining operation that are characterized by varying cutting conditions. In this regard, this paper presents a method that constructs the three-dimensional machined surface error. It is based on the consideration of the actual movements of the cutter. The cutter center positions are determined by the nominal cutter feed, cutter deflection and runout. The three-dimensional surface error map can be constructed by linking the points (x_p, y_p) calculated during the cutting force simulation process. In most models, surface error predictions were made in the direction of the axial depth of cut, that is, from the bottom to the top of the cut. The proposed method, however, readily constructs the three-dimensional surface errors.

2.2.1 Comparison of Measured and Predicted Machined Surface Errors

Figure 5(a) shows the three-dimensional machined surface profile for Test 3, which was generated during 25 revolutions of the cutter. The measured result is in good agreement with the predicted values in Figure 6. In addition, Figure 5(b) shows the two-dimensional error measured in the direction of the axial depth of the workpiece. The measured height difference (peak-to-valley value) between the maximal and minimal surface error was determined to be about 46.04 μm. The predicted height difference for this case was 47.60 μm as shown in Figure 6.



(a) Three-dimensional plot



(b) Two-dimensional plot

Fig. 5 Measured machined surface error for Test 3

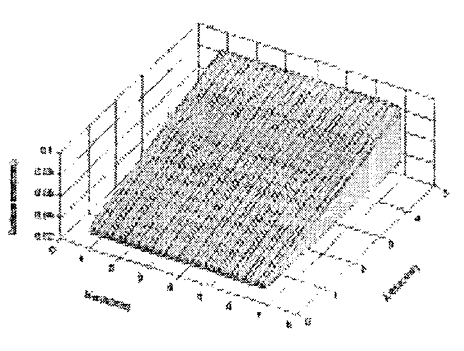


Fig. 6 Predicted machined surface profiles for Test 3

3 OFF-LINE FEED RATE SCHEDULING MODEL

This paper deals mainly with improving the machined surface quality when off-line feed rate scheduling was performed. Surface errors are generated by cutter deflection, which is influenced by cutting force. The cutting force in the y direction during one revolution, F_y, needs to be held constant to enhance the surface quality in the y direction. Thus, the relation between F_y and the feed rate is derived using the mechanistic cutting force model. The uncut chip thickness model can simplified to

$$t_c = f_t \sin\phi \tag{7}$$

where f_t is the feed per tooth. The force F_y can be approximated as Equation (8) by substituting Equation (7) into Equation (3):

$$\begin{aligned} F_y &= f_t B_1 [C_1 K_n N \sum_j \sum_k \sin(\phi-\alpha_r)\sin\phi \\ &\quad + K_f K_n C_3 N \sum_j \sum_k \sin^2\phi \\ &\quad + K_f K_n C_4 N \sum_j \sum_k \cos(\phi-\alpha_r)\sin\phi] \\ &= f_t \Phi_{total} \end{aligned} \tag{8}$$

The relationship between the feed per tooth and F_y is then

$$(f_t)_{desired} = \frac{F_y}{\Phi_{total}} \tag{9}$$

where

$$(\Phi)_{total} = B_1 C_1 K_n \Phi_1 + B_1 C_3 K_n K_f \Phi_2 + B_1 C_4 K_n K_f \Phi_3,$$

$$\Phi_1 = N \sum_j \sum_k \sin(\phi-\alpha_r)\sin\phi, \ \Phi_2 = N \sum_j \sum_k \sin^2\phi,$$

$$\Phi_3 = N \sum_j \sum_k \cos(\phi-\alpha_r)\sin\phi,$$

and N is the number of the flute.

The quantity f_t is given by Equation (10), using F_{ref} as the reference cutting force:

$$\begin{aligned} (f_t)_{desired} &= \frac{F_{ref} \times n_\theta}{\Phi_{total}} \\ &= \frac{F_{ref} \times n_\theta}{B_1 C_1 K_n \Phi_1 + B_1 C_3 K_n K_f \Phi_2 + B_1 C_4 K_n K_f \Phi_3} \end{aligned} \tag{10}$$

where $n_\theta = 360^\circ / \Delta\theta$ and $\Delta\theta$ is the cutter rotation angle increment. Thus, the optimized feed rate per revolution of the tool can be written as

$$feedrate = N \cdot RPM \cdot (f_t)_{desired} \tag{11}$$

4 GENERAL MACHINING SIMULATION

4.1 Virtual Machining System

The virtual machining system in this study can evaluate cutting performance and schedule feed rates by modifying given NC codes. Figures 7 and 8 show the conceptual structure of the virtual machining simulator and a sample computer window, respectively. The virtual machining simulator is composed of a machining database, a cutting process model, and an off-line feed rate scheduling model. The NC code and geometry information is provided using CAD/CAM software. The user supplies the machining information. Then, a simulation of the cutting process is executed to predict the cutting force and machined surface error.

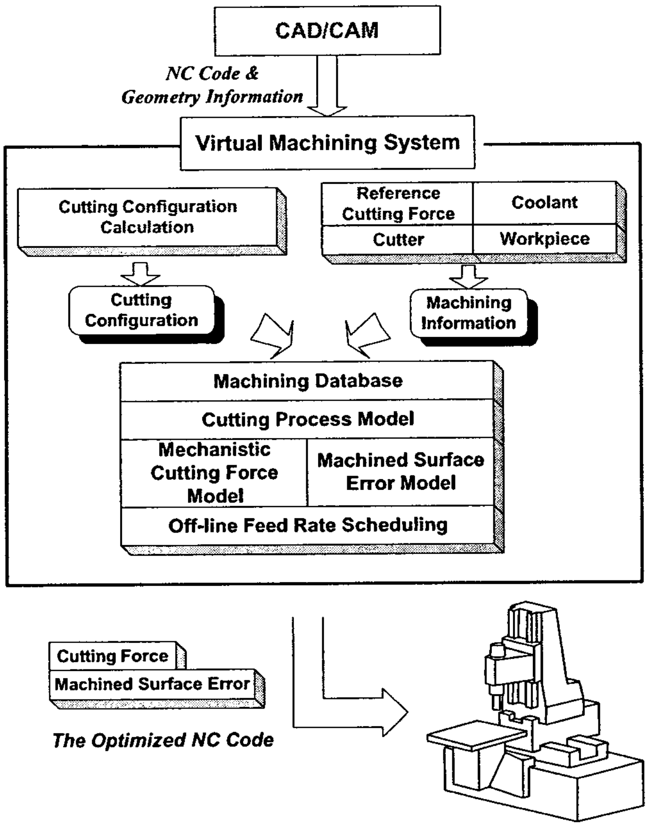


Fig. 7 The structure of the virtual machining system

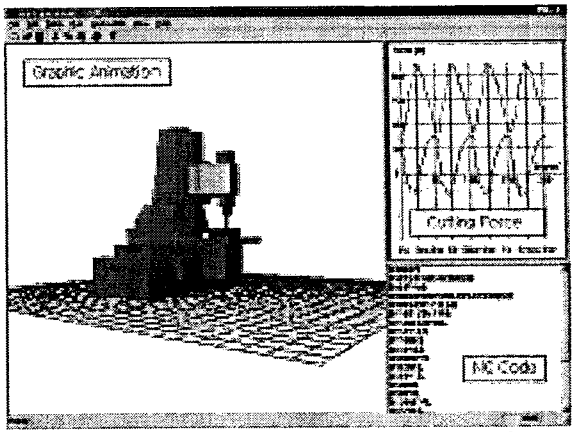


Fig. 8 The window of the virtual machining software

In most of the existing mechanistic models, in addition to the machined surface error prediction, the cutting process simulation is often restricted to a single path machining operation under a fixed cutting condition. Complex cutting processes such as die or mold manufacturing, however, are performed under two- or three-dimensional multiple tool paths. Since the tool paths in CNC machining are composed of line and arc segments, transient cuts frequently occur whenever the multiple path cutting is involved [8]. Even in steady cuts, the width of cut varies with each segment. Thus, the virtual machining system needs first to accurately compute the cutting configuration from the given NC Code. The cutting configuration, which includes the nominal position and entry / exit angle of a cutter, cutting conditions, and feed direction at the nominal cutter position, changes continuously during the transient cuts.

4.2 Application to Pocket Machining

A cutting process simulation was performed for HSS end mills with four flutes, a 30° helix angle, an 11° rake angle, and a 10-mm diameter. The workpiece material was aluminum 2014-T6. The workpiece geometry and the tool path are shown in Figure 9. The spindle speed was 1000 rpm and the original feed rate was 150 mm/min. The depth and width of the steady cut were 5 mm and 3 mm, respectively.

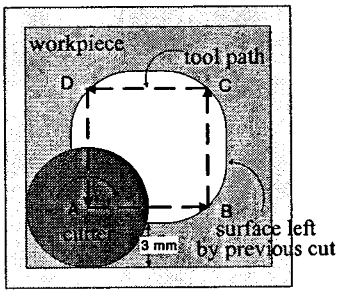
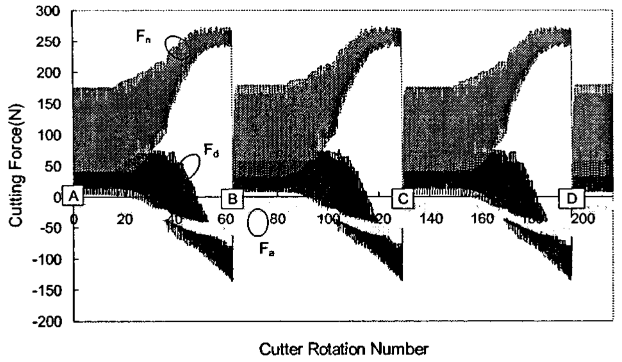
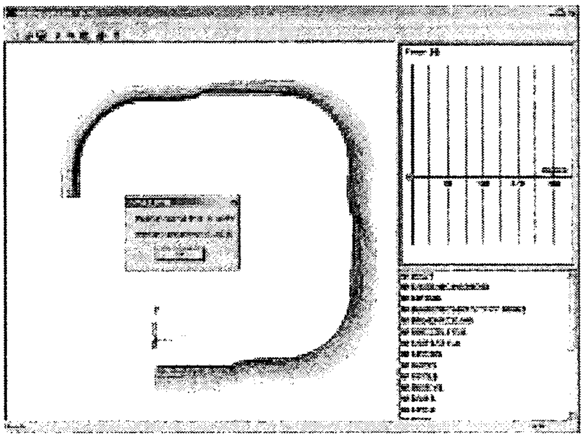


Fig. 9 Workpiece geometry and tool path



(a) The cutting forces in d-n-a coordinate
(d is feed direction, n is cross feed direction, and a is axial direction)



(b) The machined surface before feed rate scheduling
(maximum error = 118 ㎛, minimum error = 2 ㎛)

Fig. 10 The predicted results before feed rate scheduling

When the cutter enters into the corner region, the immersion angle between tool and workpiece begins to rise. The cutting forces, subsequently, increase in the corner region, thus increasing the machined surface error due to cutter deflection. Figure 10(a) shows the predicted cutting forces while machining along the tool path A-B-C-D. And Figure 10(b) illustrates the machined surface with the form error of maximum 118 ㎛. Thus, F_n, which is the cutting force normal to the machined surface and most influences the surface form error, needs to be controlled not to increase in corner region. The original feed rate can be modified to adjust this F_n according to the reference cutting force using Equation 11.

Figure 11 shows the scheduled feed rates when the reference cutting force was given as 100N. Figure 12 shows the predicted cutting force and the machined surface error when the machining was performed with the scheduled feed rate. It is shown that the average cutting force could be regulated at 100N and the overall form accuracy of the machined surface drastically improved. The maximum machined surface error was reduced to 47 ㎛, which is only 40 % of the original error.

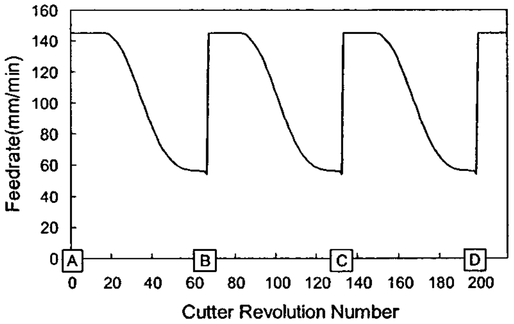
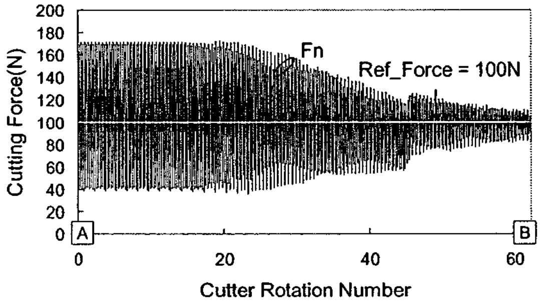
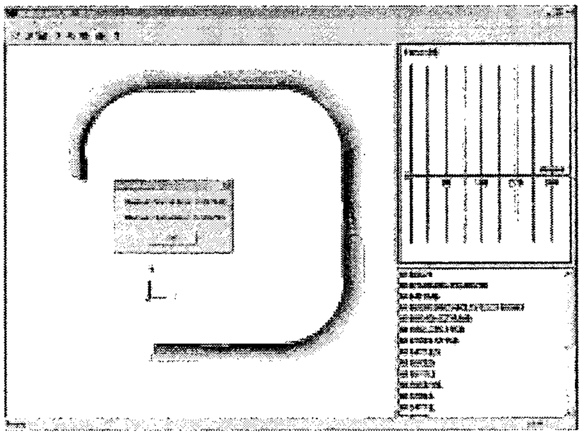


Fig. 11 The scheduled feed rate when the reference cutting force is given as 100N



(a) The cutting force in the direction normal to surface



(b) The machined surface after feed rate scheduling
(maximum error = 47 ㎛, minimum error = 2 ㎛)

Fig. 12 The predicted results after feed rate scheduling

5. CONCLUSION

Present CAM software cannot evaluate physical cutting performance, which is essential to the optimization of NC codes. Thus, selection of cutting conditions has been heavily dependent on the experience of the machinist or on the information contained in a machining data handbook.

This paper presents a virtual machining system for an evaluation of cutting performance. The functions of virtual machining system are based on the physical cutting process which evaluates cutting performance such as the cutting force and the machined surface error. The analytical model for off-line feed rate scheduling was formulated from a mechanistic cutting force model.

A software for the virtual machining simulation was developed and applied to pocket machining simulation. The virtual machining software can be successfully used to improve the productivity or accuracy of machining.

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