TOOL WEAR ESTIMATION UNDER A STRATEGY FOR CONSTANT CUTTING FORCES IN END MILLING

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Abstract This paper describes the process and utility of a method to detect cutting forces and estimate tool wear with inner sensors using a linear motor driven machining center (MC). This method is intended to realize an intelligent end-milling system. First, a mathematical prediction model for cutting forces in end milling was extended to handle cases with worn end mills. Cutting experiments using a linear motor driven MC with a static guideway showed that monitoring cutting forces and estimating tool life by utilizing the current of a feed motor were very effective without having to use the current of a spindle motor. In addition, we designed algorithms which allow the feed rate to change automatically according to the current of a feed motor. Thereby, these algorithms can maintain constant cutting forces. Experimental results using them revealed that tool life increased by restraining the progress of tool wear. Using both the mathematical prediction model and the inner sensor based on the feed motor current, one can estimate how far the tool wear progresses if the cutting engagement angle is given as a known quantity.

Key words end milling, tool wear, mathematical model, cutting force, wear estimation, inner sensor

1 INTRODUCTION

The authors, CCM Research Group, previously suggested intelligent machine tool systems for making dies and molds with high precision and high productivity. This group proposed a strategy for constant cutting forces in end milling. Contemporary strategies for constant cutting forces mainly involve optimizing tool paths and cutting conditions as NC programs before cutting so that cutting forces become constant through the use of a mathematical prediction model for cutting forces (Feed forward control) [1]. Errors in the mathematical model inevitably occur; they are caused by the increase of cutting forces resulting from the progress of tool wear. Therefore, we must estimate tool wear by monitoring cutting forces and perform adaptive tuning of cutting conditions based on wear information (Feed back control). Moreover, we must extend the mathematical prediction model for worn tools. Monitoring of cutting forces and feed back control using it has been tried with a ball screw driven MC, but it presents a serious problem: the spindle motor current must be used in combination with that of a feed motor because of low accuracy in monitoring that is attributable to great mechanical friction [2].

This paper discusses whether detection of cutting forces and estimation of tool wear are possible using only the current of a feed motor with a linear motor driven MC with a static guideway which has much less mechanical friction. Moreover, we design algorithms that enable a feed rate to change automatically according to the feed motor current and maintain constant cutting forces. We also experimentally verify the restraint of tool wear progress. Furthermore, using an extended prediction model for worn tools and a given engagement angle in combination with the inner sensor, we show that tool wear estimation becomes possible.

2 CUTTING FORCE PREDICTION MODEL

The general geometry of the end-milling operation in the case of an inner concave cut is shown schematically in Fig. 1. The maximum undeformed chip thickness and the arc length of cutting engagement are shown as t_m and L in Fig. 1, respectively [3]. In this study, response surface forms for the prediction of cutting forces are formulated and extended by assuming that the predicted value is the resultant cutting force F_{xy} in the x-y plane with three predictor variables including t_m and L shown in Fig. 1. That prediction model is expressed generally by the following quadratic polynomial:

$$F_{xy}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_{11}X_1^2+\beta_{22}X_2^2+\beta_{33}X_3^2+\beta_{12}X_1X_2+\beta_{32}X_3X_2+\beta_{13}X_1X_3\ , \tag{1}$$

where X_3 denotes the tool wear level with two given geometrical values of X_1 and X_2, which denote t_m and L, respectively. Unknown coefficients (β) are decided by experiments using least squares method.

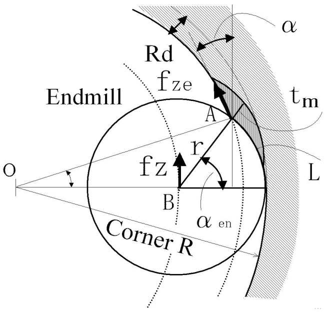


Fig. 1 Geometrical relationship in end milling

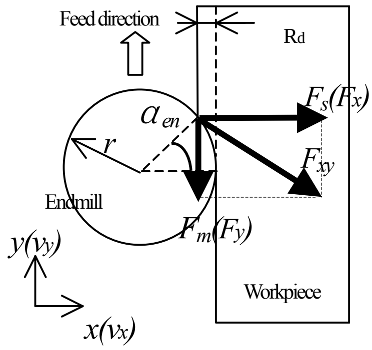


Fig. 2 Cutting force and velocity components

3 MONITORING AND CONTROL OF CUTTING FORCES USING INNER SENSORS

3.1 Monitoring Principals

The feed motor current provides a useful signal as an inner sensor: we can estimate each component of cutting forces using it. In addition, tool paths given as NC programs are already known. For that reason, we can calculate engagement angle α_{en} (i.e. arc length L) in advance.

Fig. 2 shows the relationship of each component of cutting forces in straight end milling. An algorithm for estimating cutting force components and tool wear from velocity components (feed back value) v_x and v_y for each axis, current components (feed back value), I_x and I_y, and engagement angle α_{en} are also shown in Fig. 3. Concrete steps for calculating F_m (feed direction component), F_s (the stationary direction component) and F_{xy} are shown as (a)(b)(c). Then we can estimate tool wear at that point using eq.(1) with the maximum undeformed chip thickness t_m and the arc length L (i.e. feed rate and engagement angle α_{en}).

(a) We calculate the cutting force components F_x and F_y for each axis as:

$$F_x = K_t \cdot I_x - M \cdot d(v_x)/dt - g(v_x) \tag{2}$$

$$F_y = K_t \cdot I_y - M \cdot d(v_y)/dt - g(v_y), \tag{3}$$

where K_t denotes the conversion coefficient, M is the total mass, and $g(v)$ denotes the friction force. Because of the characteristics of a linear motor driven MC equipped with a static guideway, $g(v)$ can be ignored.

(b) We calculating cutting force components F_m and F_s for each axis from cutting force components F_x and F_y and velocity components v_x and v_y. In the case of straight cutting for the y-axis direction, as shown in Fig. 3, we obtain F_m=F_y , F_s= -F_x from v_x=0.

$$F_m = \frac{v_x \times F_x + v_y \times F_y}{\sqrt{v_x^{\ 2} + v_y^{\ 2}}} \qquad\qquad F_s = \frac{v_x \times F_y - v_y \times F_x}{\sqrt{v_x^{\ 2} + v_y^{\ 2}}} \tag{4}$$

(c) We calculate the resultant cutting force F_{xy} and estimating tool wear from eq.(1).

3.2 Control of Cutting Forces

Increased tool wear engenders large temperature elevation on the end mill cutter and enlarged cutting forces.

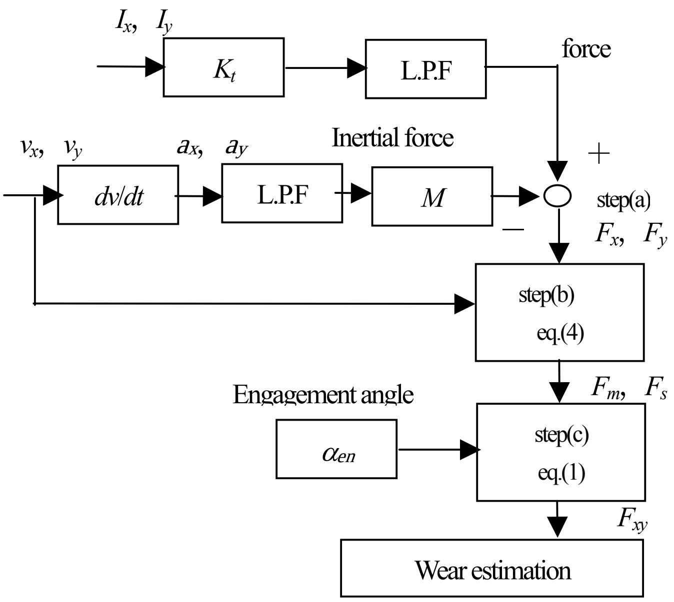


Fig. 3 Algorithm for a tool wear estimation system

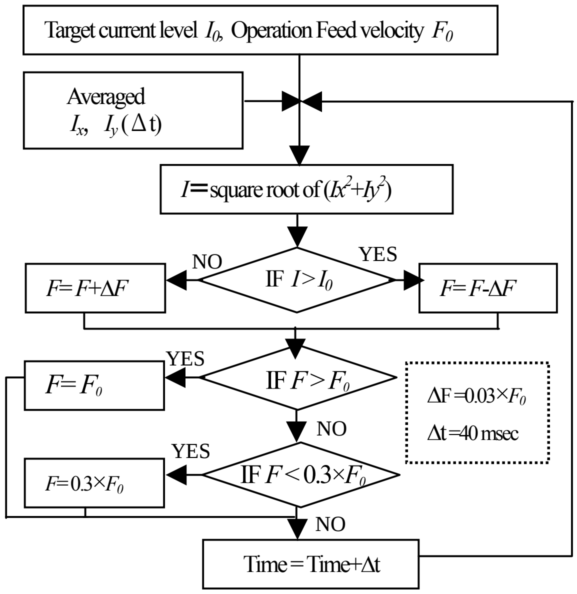


Fig. 4 Algorithm for automatic feed rate override

Consequently, there is a high rate of tool wear. We can restrain the progress of tool wear and extend the tool life by controlling the feed rate and maintaining cutting forces at a low level. In addition, it must be done under the condition of relatively good productivity. Therefore, the feed rate in end milling must be changed automatically according to the feed motor current to maintain constant cutting forces. The algorithm for that function is shown in Fig. 4. Experimental verification of whether we can restrain tool wear progress is conducted using this program installed in the NC controller.

4 EXPERIMENTAL EQUIPMENT AND PROCEDURES

4.1 End mill and Workpiece Material

An (Al,Ti)N-coated micro-grain carbide radius end mill with a diameter of 8 mm, a 45° helix angle and six flutes was used in these experiments. Hardened steel (JIS SKD61) with HRC53 hardness was chosen as the workpiece material. In addition, an (Al,Ti)N-coated HSS radius end mill with a diameter of 8 mm and stainless steel JIS SUS430 was used for the experiment of detection of flank wear V_B.

4.2 Experimental Equipment and Procedures

The workpiece (SKD61) was set on the table of a linear motor driven MC with a static guideway, as shown in Fig. 5. The workpiece was mounted on a three-axis dynamometer that was used to measure the cutting forces. The feed motor current (feed back value) was also measured simultaneously.

Cutting force measurements were done by both straight and corner cutting with constant axial and radial depths of cut. Wear experiments were done by straight cutting. Table 1 shows the cutting conditions for the wear experiment. Providing the same axial and radial depth of cut, the straight cutting is repeated for the same direction. These procedures were repeated until the tool life of the end mill was reached.

Table 1 shows the standard cutting conditions at the measurements of cutting forces. In case of corner cutting, feed rate and radial depth of cut are changed according to the radius of workpiece based on the values of t_m and L under standard cutting conditions.

4.3 Measuring Points and Response Surfaces

In experiments for formulating the response surfaces, the equiradial design of eight measuring points ($P_i = (\sqrt{2}\cdot\cos(\pi\cdot(i-1)/4),\ \sqrt{2}\cdot\sin(\pi\cdot(i-1)/4))$, (i=1,2,...8)) with the origin in the plane of coded variables X_1 and X_2(t_m and L) is used. X_1, X_2 are normalized by X_1=(t_m−t_{m0})/δt_m, X_2=(L- L_0)/δL; $\delta t_m$and δL are 11 μm and 0.349 mm, respectively. Normalized tool wear level X_3 is represented by three levels, such as X_3=0,1,2 from a new tool to a worn tool. A quadratic polynomial with three variables is finally formulated using data in each level. As shown in our previous study [4], the normal cutting force component, F_x, increases extremely with the progress of tool wear in end milling hardened steel. Therefore, we presume three steps of X_3 as (0) new tool, (1) F_x becomes 1.5 times the initial value, and (2) F_x becomes 2.0 times the initial value (worn out tool).

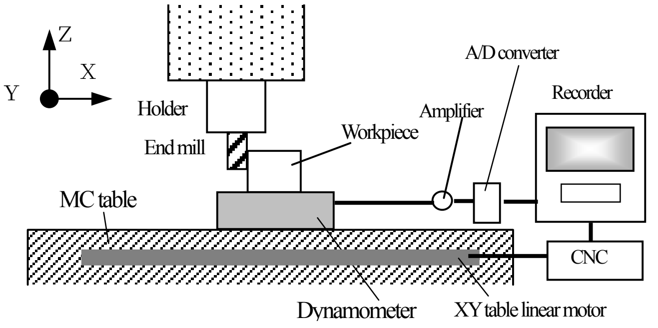


Fig. 5 Setup for experiments

Table 1 Standard cutting conditions for experiments (End mill diameter: 8 mm)

Cutting speed (Spindle speed)	302 m/min ($12000\ min^{-1}$)
Feed per tooth	0.07 mm/tooth
Cutting direction	Down cut
Free length of end mill	24 mm
Tool runout	≦7 μm
Radial depth of cut	0.4 mm
Axial depth of cut	8 mm
Workpiece	Die steel SKD-61(HRC53)
Coolant	Dry air
Chip thickness(standard) t_{m0} Engage length(standard) L_0	30.5 μm 1.80 mm

5 EXPERIMENTAL RESULTS AND INTERPRETATIONS

5.1 Detection of Cutting Forces

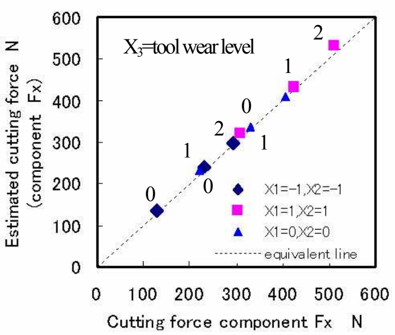
Measured cutting forces by straight cutting for three measuring points for formulating the response surfaces are shown in Figs. 6(a)–6(c). Wear level is also shown as X_3=0,1,2. Here, the measured cutting force (the horizontal axis) means the value measured by the three-axis dynamometer, whereas estimated cutting force (the vertical axis) shows the value estimated by the currents of feed motors proposed in the previous chapter 3.1. Straight cutting for the y-axis direction, as that shown in Fig. 3, means that the cutting force component for feed direction is F_y, and that for the stationary direction is F_x. These figures show that we can estimate cutting forces excellently using feed motor current for all components and resultant cutting force F_{xy}. Effective estimation of cutting forces utilizing the currents of feed motors is possible without having to use the spindle motor current. These measurements also show that we can monitor the static change of cutting forces that occurs because of tool wear or a large and middle sized chipping of the cutting edge. Table 2 shows coefficients β of the response surface and statistical values.

Moreover, as an example of corner cuttings, spiral end milling is conducted with the maximum undeformed chip thickness t_m and the arc length L fixed constant. Measured and estimated cutting forces by spiral end milling are shown in Figs. 7(a)–7(b). These figures illustrate that the estimated values coincide excellently with measured values, revealing that an effective estimation of cutting forces is also possible in corner cuttings.

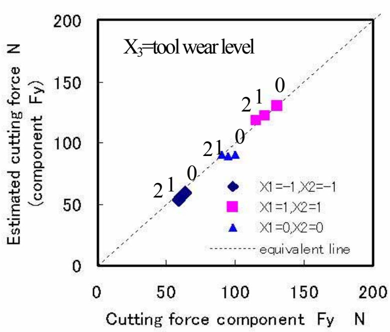
5.2 Detection of flank wear V_B

The width of flank wear V_B is generally used as an indicator of tool wear, which is suitable for direct measurement and observation of tool wear. As the width of flank wear V_B can be judged by cutting forces, we verified the estimation system experimentally. To simplify the problem, we compare the initial cutting force F_{new} and the cutting force with worn tool F_w as the following equation, which is often used in tapping and drilling[5][6]. W_f in eq.(5) is a tool wear coefficient. The reluctant cutting force F_{xy} is used for F_{new} and F_w.

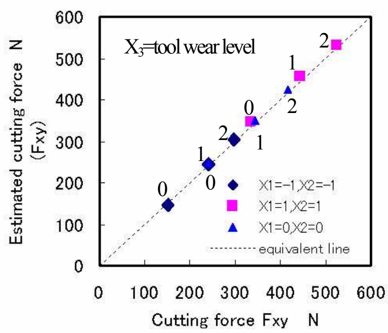
$$F_w = (1+W_f) \cdot F_{new} \qquad (5)$$



(a) Cutting force component F_x



(b) Cutting force component F_y

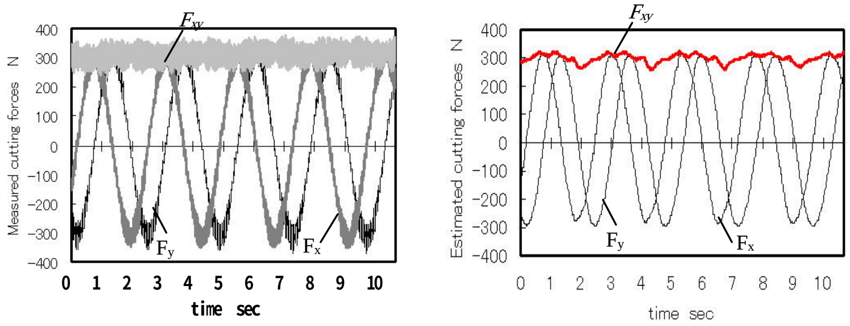


(c) Resultant cutting force F_{xy}

Fig. 6 Relation between measured and estimated values of cutting forces

Table 2 Coefficients of response surface by X_1, X_2, X_3 (F_{xy})

Term	Coefficient values	F ratio
Intercept	236.3	-
X_1	54.04	3542
X_2	40.15	2239
X_3	105.2	1262
X_1^2	−10.93	30
X_3^2	−11.96	42
X_1X_2	25.76	106
X_1X_3	2.937	19
X_2X_3	8.360	299
R^2	0.9968	
R_a^2	0.9951	



(a) Measured (b) Estimated

Fig. 7 Measured and estimated cutting forces in spiral end milling

The width of flank wear V_B can be judged by the tool wear coefficient W_f defined in eq.(5). Tool life is judged to have been reached when the tool wear coefficient W_f becomes greater than a threshold level. Fig. 8 shows the tool wear coefficient W_f estimated by eq.(5) using the currents of feed motors in straight side cutting of stainless steel JIS SUS430. A measured width of flank wear V_B in the interval of cutting is also shown in the same figure. Cutting conditions are the following: spindle speed=1000 rpm: feed rate=0.03 mm/cutter: radial depth of cut=0.5 mm: axial depth of cut =8 mm: and so forth. The tool wear coefficient W_f estimated by cutting forces almost parallels a width of flank wear V_B, which reveals that we can judge tool wear and tool life using this method. The width of flank wear V_B=0.14 mm is reached when W_f=1.6, tool life is judged to reach at this point. The appearance of a cutting edge of the worn out (Al,Ti)N-coated HSS radius end mill is shown in Fig. 9.

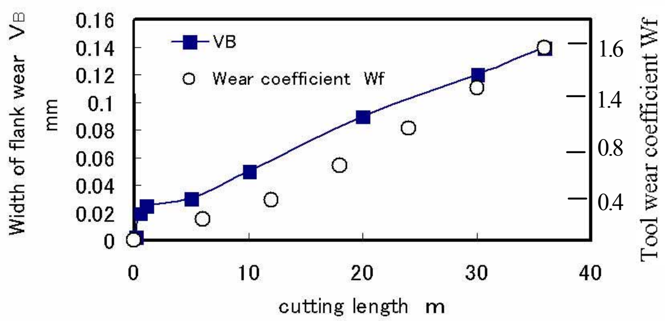


Fig. 8 Relation between cutting length and width of flank wear V_B, wear coefficient W_f

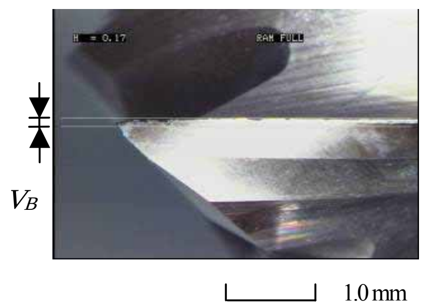


Fig. 9 Appearance of worn cutting edge (cutting length=36 m; V_B=0.14 mm)

5.3 Restraint of tool wear

Fig. 10 shows the relationship between cutting length and cutting forces and the relationship between cut length and actual feed rate which were obtained in the wear experiment on the condition that the feed rate changes automatically according to the current of feed motor to maintain cutting forces constant. The wear experiment with a constant feed rate was conducted for comparison and the results are also shown in Fig. 10. The experimental result shows that the tool life (cutting length) was increased as much as 30% from 192 m to 264 m. The actual feed rate was decreased 65% compared to the initial value when the tool life was reached and total cutting time increased 30%. So it has become clear that we can restrain tool wear using the method in the reasonable range of decreased efficiency. In this experiment, radial depth of the cut is always constant, but the maximum chip thickness changes according to the feed rate change. If we assume the cutting force F_{xy} and the arc length L(i.e. engagement angle α_{en}) are kept constant in eq.(1), then we obtain the relationship between the maximum chip thickness t_m and the tool wear level, as shown in Fig. 11. The maximum chip thickness t_m can be converted easily to feed rate(feed velocity F). Using this relationship, one can estimate tool wear progress from the actual feed rate at that point in end milling.

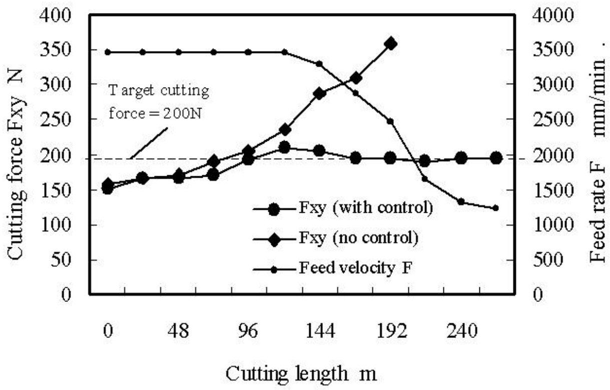


Fig. 10 Relation between cutting length and cutting forces, controlled feed velocity

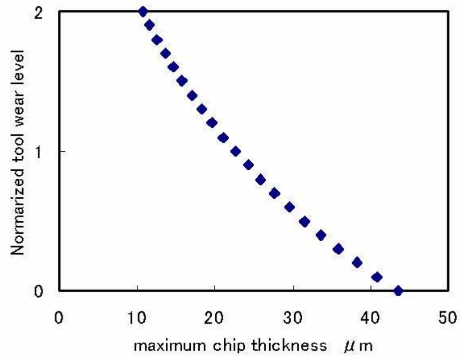


Fig. 11 Relation between the maximum chip thickness and tool wear level(F_{xy}=200 N, L=1.80 mm(L_0))

6 CONCLUSIONS

The following conclusions can be obtained from this study.

1) In case of a linear motor driven MC with a static guideway, the monitoring cutting forces using the current of a feed motor were quite effective without having to use the current of a spindle motor.

2) Monitoring cutting forces using the feed motor current was quite effective, but also in corner cutting such as spiral end milling, not only in straight cutting.

3) One can estimate the width of flank wear V_B and judge tool life using the tool wear coefficient W_f , which is estimated by the initial and present value of cutting forces using the currents of feed motors.

4) The tool life increased 30% in the wear experiment on the condition that feed rate changes according to the feed motor current to keep cutting forces F_{xy} constant. One can restrain the tool wear progress using this method in the reasonable range of decreased efficiency.

5) Using both the mathematical prediction model and the inner sensor based on the feed motor current, one can estimate the extent to which tool wear progresses only with the given engagement angle α_{en}.

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