Influence of Die Geometry on Tool Life in Endmilling of Hardened Steel

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Abstract High speed cutting of hardened steel SKD61(HRC53) became possible by the introduction of a sintered carbides endmill coated by (Al,Ti)N. According to machining experiments, typical tool life of this endmill cutter is about 320 m for straight line cutting. It becomes, however, only 30 m for inner cylindrical surface cutting of the radius ratio ro/r = 2 (r: cutter radius, ro: machined geometry radius), which is often used for the machining of die/mold. This short tool life is caused by the rapid increase of cutting force, temperature elevation on the cutting tool, and chip jamming, all of which are easily introduced at inner curve cutting. By applying the constant cutting force control technique, the tool life can be elongated to 110 m. To regulate the cutting force at a constant level, the feed forward control is used based on a mathematical model of cutting force.

Key words endmill, hardened steel, die/mold, tool life, constant force cutting

1. INTRODUCTION

One of the most important process parameters in the machining of dies and molds is the tool life. The tool life is typically defined as the total machining length in straight milling under standard cutting conditions. In practice, however, most dies and molds have a three-dimensional free-form surface. In order to properly machine such a surface, cutting conditions must be modified according to the product geometry. In this paper, we first conduct machining tests to investigate the influence of the curvature radius on the tool life in two-dimensional end milling processes. Then, by using a prediction model of cutting forces, machining conditions are optimized such that the cutting force is regulated at the given constant level over the whole path. Even in the machining of a free-form surface, the tool life can be extended by regulating the cutting force. In order to validate the effectiveness of the cutting force control, the results of machining tests under the constant cutting force control are compared with the cases where machining conditions are fixed over the entire process.

2. PREDICTION MODEL OF CUTTING FORCES FOR STRAIGHT ENDMILLS

This section outlines a mathematical model to predict cutting forces in end milling processes, which will be used for the cutting force control. The relationship of geometric parameters in internal cylindrical machining are illustrated in Figure 1, where R is the curvature radius of the machined surface and R_d is the radial depth of cut. In the figure, t_m and L respectively denote the maximum undeformed chip thickness and the arc length of cutting engagement. In this paper, we use the response surface model with the variables t_m and L to predict the combined cutting force, F_{xy}, on the XY plane. F_{xy} is defined as the maximum cutting force while all the tool edges interfere with the engagement angle, α_{en}. To simplify the response surface model, the following polynomial model is used:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2$$

where Y represent the predicted cutting force, F_{xy}, and X_1 and X_2 represent t_m and L, respectively. Six coefficients, β_0, …, β_{12}, can be identified by conducting a set of straight milling tests.

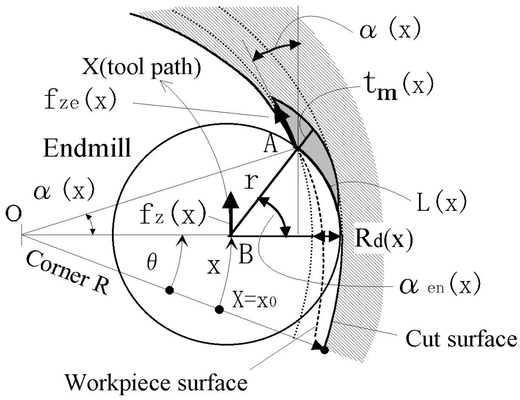


Fig. 1 General tool path model with varying radial depth of cut

3. EXPERIMENTAL PROCEDURE

3.1 Experimental Setup

The machining experiments presented in the following sections were conducted on a machining center. An (Al-Ti)N-coated sintered carbide end mill of the diameter 6 mm (six flutes) was used. The workpiece material was a hardened steel, SKD61(HRC53). Figure 2 depicts an overview of the experimental setup. The Workpieces 1 and 2 of the same material are set on a table of a vertical-type machining center. The Workpiece 2 is installed on a piezoelectric three-component dynamometer, such that the cutting force can be measured on this workpiece. In the following experiments, the Workpiece 1 is machined continuously for some distance, and then the cutting force is measured by machining Workpiece 2 under exactly the same machining conditions. Then, the wear on tool edges is observed. These steps are repeated until the end of the tool life is reached.

The criteria to judge the tool life, and devices to measure them, are summarized as follows:

1) The wear on tool edges (after every 10 m of machining length, the tool edges are observed by using a CCD camera. If necessary, a non-contact type microscope with automatic optical focusing can be used to observe the edge surface geometry)
2) Chips (observe their shape and color by using a tool microscope).
3) Cutting forces (after every 10 m of machining length, the cutting force is measured by a three-component dynamometer).

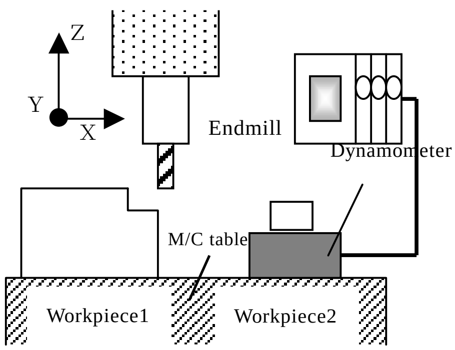


Fig.2 Setup for experiments

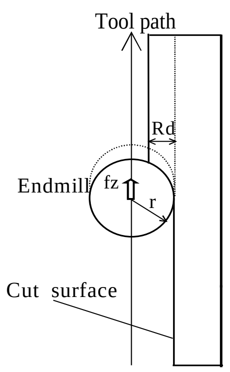


Fig.3 Workpiece A

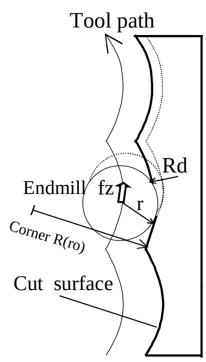


Fig.4 Workpiece B

3.2 Machining Tests under Fixed Machining Conditions

In this experiment, all the machining conditions are fixed over the entire process, as shown in Table 1. The feedrate is set to the standard value, which is given based on straight milling tests.

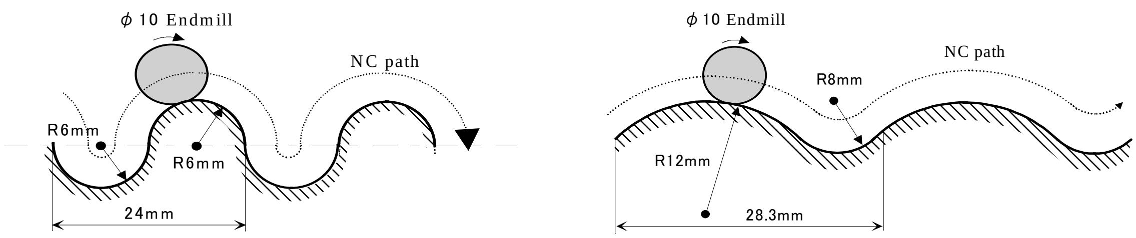
In the straight milling test, the Workpiece A is machined on a straight path to the Y direction with fixed radial and axial depth of cut, as shown in Figure 3. This is repeated to the same direction with the same radial depth of cut until the end of the tool life is reached. Similarly, in circular path milling tests, the wave-shaped surface of the same curvature radius is repeatedly machined until the end of the tool life is reached, as illustrated in Figure 4. This test is repeated with changing the radius ratio(*ro*/*r*), i.e. the ratio of the tool radius (*r*) and the curvature radius of the workpiece surface (*ro*). The objective of this experiment is to investigate the influence of the radius ratio (at minimum *ro*/*r=1.2*) on the tool life.

Table 1 Cutting conditions for wear experiments

Cutting speed V (Spindle speed S)	302 m/min (9600 min^{-1})
Feed rate f_z <Standard> (Feed rate F in NC program)	0.1 mm/tooth (5760 mm/min)
Cutting direction	Down cut
Free length of endmill	30 mm
Tool runout	≦ 7 μm
Radial depth of cut R_d	0.5 mm
Axial depth of cut A_d	10.0 mm
Coolant	Dry air

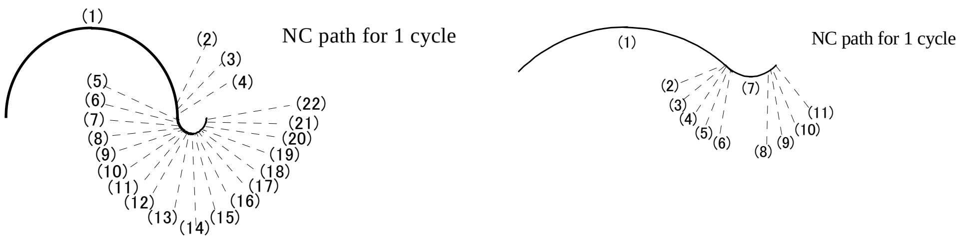
3.3 Machining Tests under Constant Cutting Force Control

By using the same experimental setup, similar tool wear tests were conducted under the condition where the cutting force is regulated at given constant level over the whole path. Two tool paths used in this experiment, as shown in Figure 5. By using the prediction model of cutting force presented in Section 2, the feedrate profile can be optimized along the path such that the cutting force is regulated at the given constant level. The optimized feedrate profile is shown in Figure 6 and Table 2.



(A) (B)

Fig.5 Wave form paths



(A) (B)

Fig.6 Optimal feedrate for constant cutting force control

In tool wear tests, the Workpiece 1 in Figure 2 is machined along each wave shaped path (Figure 5) to the Y-direction with the constant axial depth of cut. This is repeated by progressing the path to the X-direction by the same pitch at each cycle. After the machining length on the Workpiece 1 reaches 35m~45m, the Workpiece 2 is machined with the same tool and conditions in order to measure the cutting force (the cutting force can be measured whenever is necessary). Then, the wear on tool edges are observed. These steps are repeated until the end of the tool life is reached. Note that the machining length is defined as the total length of the machined workpiece surface.

For the comparison, the same tool wear test is conducted by using the same wave shaped paths, but with the constant tool center feedrate (i.e. fixed machining conditions). Note that the feedrate in this test was determined such that the material removal rate per unit time became the same as that in the constant cutting force case.

Table2 Optimal federate for constant cutting force control

(A)

No.	Path length (mm)	Command F * (mm/min) (i) Controlled feed rate	Command F * (mm/min) (ii) Constant feed rate
(1)	34.3	F12124	F4320
(2)	0.1	F2857.5	〃
(3)	0.1	F1306.8	〃
(4)	0.1	F809.1	〃
(5)	0.175	F644.6	〃
(6)	0.175	F574.4	〃
(7)	0.175	F547.9	〃
(8)	0.175	F548.5	〃
(9)	0.175	F569.9	〃
(10)	0.175	F610.2	〃
(11)	0.175	F670.4	〃
(12)	0.175	F754.2	〃
(13)	0.175	F868.1	〃
(14)	0.175	F1023.6	〃
(15)	0.175	F1240.5	〃
(16)	0.175	F1555.2	〃
(17)	0.175	F2040.1	〃
(18)	0.175	F3414.7	〃
(19)	0.175	F5413.1	〃
(20)	0.175	F12124	〃
(21)	0.175	F12124	〃
(22)	0.175	F12124	〃

(B)

No.	Path length (mm)	Command F * (mm/min) (i) Controlled feed rate	Command F * (mm/min) (ii) Constant feed rate
(1)	24.0	F8689.9	F4320
(2)	0.489	F8302.2	〃
(3)	0.521	F7083.	〃
(4)	0.5	F5250.1	〃
(5)	0.5	F3346.1	〃
(6)	0.5	F1583.6	〃
(7)	3.83	F1583.6	〃
(8)	0.39	F1871.6	〃
(9)	0.433	F3277.4	〃
(10)	0.283	F4853.4	〃
(11)	0.23	F8689.9	〃

4. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 7 summarizes the relation of the corner radius and the measured tool life in internal cylindrical machining tests. The tool life in circular milling became much shorter than that in straight milling. It can be also observed that there is a significant change in the trend of the tool life around the corner radius of 6mm~8mm. In this region, the ratio of the corner radius and the tool radius is as small as 1.2~1.6, and thus the arc length of cutting engagement per a tooth becomes much larger than that in straight milling. The tool life becomes much shorter in this region not only because of the rapid progress of normal tool wear, but also because of the difficulty in chip removal, or the increase of the cutting heat and cutting force. These results suggest that the design of machining conditions is a critical issue in free-form surface milling, especially in cavity milling. In the following experiments, in order to validate the influence of cutting force on the tool life, the constant cutting force control is applied to extend the tool life even when the radius ratio is small.

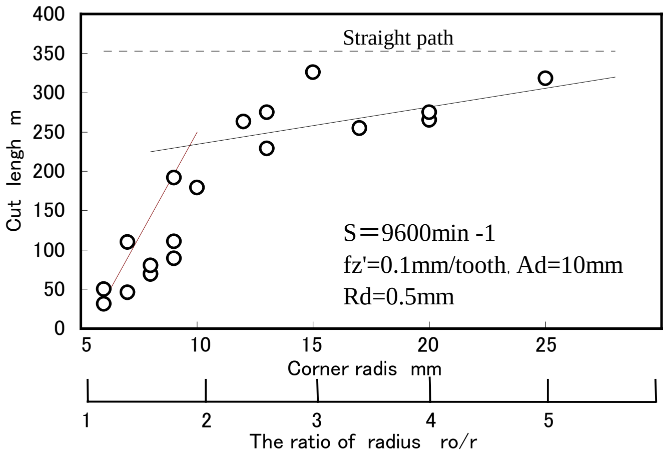
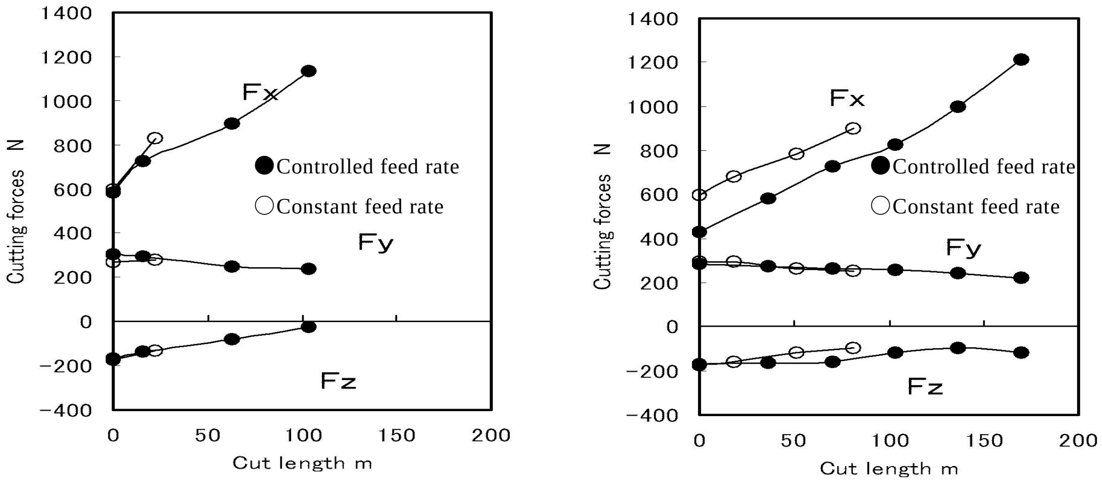


Fig.7 Measured relationship between the corner radius and the tool life

Figure 8 plots the change of measured cutting forces until the end of tool life in tool wear tests on the wave shaped paths (A) and (B). It can be observed in both cases that only the normal cutting force significantly increases as the cutting length increases. In the experiments, sparks were observed in both cases when the internal arcs are machined, and the sparks gradually grew as the cutting length increased. In both cases, the end of the tool life was reached due to the



(a) Waveform path (A) (b) Waveform path (B)

Fig.8 Change of cutting force components in waveform path experiments

welding that occurred at bottom edges of the tool.

Figure 9 summarizes the tool life in the experiments on the wave shaped paths (A) and (B). The tool life in the straight milling test is also shown for the comparison. In the case of (A), the tool life (total cutting length) was extended by approximately five times by controlling the feedrate. Similarly, in the case of (B), the tool life was elongated by about two times. Recall that the radius ratio in the path (B) is not as small as that in the path (A). If the radius ratio is further larger, the machining conditions can be regarded close to those in straight milling. In such a case, it can be predicted that the tool life gets closer to that in the straight milling case shown in Figure 9.

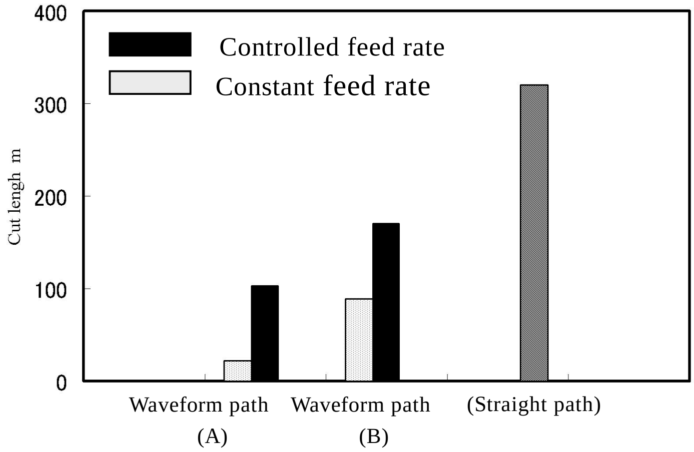


Fig.9 The relationship between the path geometry and the tool life

These experimental results show that the cutting force control is particularly effective to extend the tool life when many internal cylindrical surfaces of small curvature radius are included in the milling path.

5. CONCLUSION

This paper studied the influence of the path geometry on the tool life in two-dimensional end milling of hardened steel by a straight end mill. In particular, the tool life in internal cylindrical surface milling processes of small radius ratio was compared with straight milling cases. The following conclusions are drawn based on experimental results:

1) When the machining conditions are fixed over the whole path in circular milling, the tool life became much shorter than straight milling cases, particularly in the region with the radius ratio 1.2~1.6.
2) For internal cylindrical surface milling processes of small curvature radius (1.2≤ radius ratio $ro/r \leq 2.0$), the response surface model to predict, and control, the cutting force was presented. Two parameters, the maximum undeformed chip thickness, t_m, and the arc length of cutting engagement, L, were chosen as the determining variables. They can be computed from the geometry of the tool path and workpiece surface.
3) The cutting force control (by optimizing the feedrate) was particularly effective to extend the tool life when many internal cylindrical surfaces of small curvature radius are included in the milling path.

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