Monitoring of Machining Error Caused by Deflection of End-Mill Using Indirect Methods

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Abstract: The purpose of this study is a real-time compensation of the machining error caused by deflection of a small diameter end-mill at a cutting point. Then, the growth mechanism of machining errors in end-milling was investigated by comparing measured deflection of tool and cutting forces with machining errors. As a result, it was found in the experiments that relation between deflection of tool at cutting point and normal force under cutting process could be estimated from static stiffness. In addition, it was concluded that machining errors in up milling could be estimated from minimum value of distance from cutting edge to ideal machined surface.

Keywords: Straight Fluted End-Mill, Machining Error, Monitoring, Cutting Force, Deflection of End-Mill

1. Introduction

In recent years, machining centers have been used widely in metal mold manufacturing process because high speed machining by using a small diameter end-mill was put into practical use. However, since depression of metal molds used for injection molding is complex and fine in form and it has a large difference in depth, long end-mills with a small diameter have to be used in metal mold machining process. Then use of the long end-mill with a small diameter degrades machining accuracy of metal mold in form, since it deflects on a large scale at a cutting point due to cutting forces. Furthermore, it is pointed out that the static stiffness of end-mill and other support systems greatly influences the machining error in sideway cutting with a square end-mill[1-3]. Therefore, the system that degrades the machining error by compensating the deflection of end-mill has been proposed until now[4]. However, the method by which it can compensate more easily for the deflection of the end-mill at a cutting point is expected because it is not suitable for practical use though this system is unique.

The purpose of this study is a real-time compensation of the machining error caused by deflection of a small diameter end-mill at a cutting point. For this final purpose, in this research, the growth mechanism of machining errors in end-milling was investigated by comparing measured deflection of tool and cutting forces with machining errors.

2. Experimental Procedure

2.1 Experimental Apparatus and Conditions

Cutting tests were carried out on a vertical machining center. Experimental apparatus used in this study is shown in Fig.1 and cutting conditions are shown in Table 1. A plate-shaped workpiece of 10mm in thickness was milled in up milling at its end face by a milling cutter moving in the horizontal direction. The workpieces were made of a brass plate. The groove of 2mm in depth and 4mm in width was milled on the surface of the workpiece before cutting tests as shown in Fig.2. Relation between cutting force, deflection of tool and machining error was investigated efficiently in experiments by slanting the workpiece at the angle of 7 degrees because the slanted workpiece made the axial depth of cut continuously increase with progress of cutting. The cutting force $F_x$ in the feed direction and the cutting force $F_y$ in the direction

![Figure 1: Experimental apparatus](image)

Table 1: Experimental conditions

<table>
<thead>
<tr>
<th>Workpiece Material</th>
<th>60-40 Brass (JIS C2801P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool Type</td>
<td>Straight Fluted End-Mill</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>12</td>
</tr>
<tr>
<td>Number of teeth</td>
<td>1</td>
</tr>
<tr>
<td>Spindle speed (N/m)min⁻¹</td>
<td>1200</td>
</tr>
<tr>
<td>Feed rate (μm/rev)</td>
<td>100, 150</td>
</tr>
<tr>
<td>Type of cut</td>
<td>Up milling</td>
</tr>
<tr>
<td>Radial depth of cut (b mm)</td>
<td>1.0, 1.5</td>
</tr>
<tr>
<td>Axial depth of cut (t mm)</td>
<td>0 ~ 6.0</td>
</tr>
</tbody>
</table>
were transmitted to a personal computer through a A/D converter. In cutting tests, end-milling cutter began to move apart from a workpiece and approached it. Consequently the signal collecting started at the moment when the axis of an end-milling cutter reached at the left end face of the workpiece. The start point of measurement was detected by a photoelectric sensor fixed on the spindle head as shown in Fig.1. After each cutting test, machining errors of machined surface were measured on machine with a contact-type displacement sensor fixed on the spindle head of a machining center.

2.2 Static Stiffness of End-Mill

In measurements of static stiffness, a workpiece is fixed on a dynamometer as shown in Fig.1. The load was measured with the dynamometer while gradually increasing the deflection of tool at cutting point controlled by NC. In addition, the deflection of tool was measured with the Gap sensor.

Figure 3 schematically illustrates the bottom view of tool in measurement of static stiffness. Radial direction of peripheral cutting edge is normal to the feed direction of tool. Figure 4 shows relation between deflection \( \delta_g \) of tool at Gap sensor and deflection \( \delta_e \) of tool at cutting point. Here, deflection \( \delta_e \) of tool at cutting point is moved distance of table. This relation can be expressed as follows.

\[
\delta_e = K \cdot \delta_g
\]  

In the following, "deflection of tool at cutting point" is expediently written "deflection of tool end" in this paper.

Figure 5 shows relation between load \( F \) and deflection \( \delta_e \) of tool end. In both directions of load, the deflection of tool end increases with increase in the load. However, there is difference between inclinations in the direction of X and the direction of Y. This difference is caused by the difference of cross sectional shape of tool as shown in Fig.3. In addition, the deflection of tool end in the direction perpendicular to the direction of load was measured with a Gap sensor. The deflection of tool end in the direction perpendicular to the direction of load is about 1 to 4% of the deflection of tool end in the direction of load.
load. Therefore, the deflection of tool end in the direction perpendicular to the direction of load can be neglected. The relation in the direction of Y can be expressed as follows.

\[ \delta_y = K_F \cdot F_y \]  

(2)

3. Experimental Results

3.1 Deflection of Tool, Machining Error and Normal Force to Distance from Workpiece End Face

Figure 6 shows deflection \( \delta_y \) of tool at Gap sensor, machining errors \( e_y \) and normal forces \( F_y \) with progress of cutting. Both the maximum value of normal force \( F_y \) and the maximum value of deflection \( \delta_y \) of tool linearly increase with increase in axial depth of cut. On the other hand, the machining error \( e_y \) exponentially increases with increase in axial depth of cut.

3.2 Relation between Machining Error and Deflection of Tool End

Figure 7 schematically illustrates cross sectional view of cutting process in up milling. Here, point A is a position at the moment when radial direction of peripheral cutting edge is normal to the feed direction of tool.

Figure 8 shows deflections of tool end while the spindle makes 2 rotations. Here, \( (K_\delta \delta_y)_{\text{max}} \) is the maximum value of deflection \( K_\delta \delta_y \) of tool end, and \( (K_\delta \delta_y)_n \) is a deflection \( K_\delta \delta_y \) of tool end at the moment when radial direction of peripheral cutting edge is normal to the feed direction of tool as point A shown in Fig.7.

Figure 9 shows change of deflection \( K_\delta \delta_y \) of tool end to distance \( L \) from workpiece end face. Deflection \( (K_\delta \delta_y)_{\text{max}} \) of tool end linearly increases with increase in axial depth of cut. On the other hand, deflection \( (K_\delta \delta_y)_n \) of tool end exponentially increases with increase in axial depth of cut such as the result of machining error \( e_y \) in Fig.6. Consequently, it is thought that machining error can be estimated not from maximum value of deflection of tool end but from deflection of tool end at the moment when radial direction of peripheral cutting edge is normal to the feed direction of tool.

Figure 10 shows relation between machining error \( e_y \) and deflection \( K_\delta \delta_y \) of tool end. There is no correlation between machining error \( e_y \) and deflection \( (K_\delta \delta_y)_{\text{max}} \) of tool end. On the other hand, it is thought that deflection \( (K_\delta \delta_y)_n \) of tool end can be related with machining error \( e_y \).
because the deflection \( (K_d \delta_g) \) of tool end linearly increases with increase in machining error \( e_y \). However, difference between deflection \( (K_d \delta_g) \) of tool end and machining error \( e_y \) is not small.

Figure 11 shows change of cutting edge position to rotational angle in up milling. Two characteristic figures are selected from the results. The solid line represents the cutting edge position without deflection of tool. Open mark represents the deflection \( (K_d \delta_g) \) of tool end. And the solid mark represents the sum of the value shown by the solid line and the value shown by the open mark. That is, solid mark represents the distance \( D_d \) from cutting edge to ideal machined surface. The cutting edge is closest to machined surface at the rotational angle of –1.8 degrees in upper figure. And the cutting edge is closest to machined surface at the rotational angle of –3.6 degrees in lower figure. Consequently, it is found that the rotational angle at the moment when cutting edge is closest to machined surface changes on account of cutting conditions.

Figure 10: Relation between machining error and deflection of tool end

Figure 11: Change of cutting edge position to rotational angle

3.3 Relation between Machining Error and Normal Force

Figure 13 shows normal force \( F_y \) while the spindle makes 2 rotations. Here, \( (F_y)_{\text{max}} \) is the maximum value of normal force \( F_y \), and \( (F_y)_{\text{n}} \) is a normal force at the moment when radial direction of peripheral cutting edge is normal to the feed direction of tool as point A shown in Fig.7.

Figure 12: Relation between machining error and minimum value of distance from ideal machined surface

Figure 13: Normal force in detail
from workpiece end face. Normal force \((F_y)_{\text{max}}\) exponentially increases with increase in axial depth of cut such as the result of deflection \(K_{\delta} \delta_f\) of tool end in Fig.9.

Figure 15 schematically shows cutting situations when undeformed chip thickness gradually increases with progress of cutting[5]. Fig.15(a) shows a situation when cutting edge only comes in contact with workpiece elastically. Fig.15(b) shows a situation when workpiece surface begins to deform plastically by cutting edge. Fig.15(c) shows a situation when chip begins to flow. Consequently, it is thought that cutting edge begins to produce finished surface from the moment when chip begins to flow. Because of this mechanism, it is thought that deflection of tool end and normal force at the moment when radial direction of peripheral cutting edge is normal to machined surface exponentially increase with increase in axial depth of cut as shown in Fig.9 and Fig.14.

Figure 16 shows relation between maximum value \((F_y)_{\text{max}}\) of normal force and maximum value \((K_{\delta} \delta_f)_{\text{max}}\) of deflection of tool end. In this figure, relation between load \(F\) and deflection \(\delta_f\) of tool end obtained in measurements of static stiffness is also represented by the solid line. In all conditions, the deflection \((K_{\delta} \delta_f)_{\text{max}}\) of tool end linearly increases with increase in the maximum value \((F_y)_{\text{max}}\) of normal force on the solid line. Consequently, it is concluded that deflection of tool end can be estimated from normal cutting force by using static stiffness.

Figure 17 shows relation between machining error \(e_y\) and deflection \(K_{\delta} F_y\) of tool end estimated from normal force. Deflection \((K_{\delta} F_y)_{\text{max}}\) of tool end linearly increases with increase in machining error \(e_y\) such as the result of deflection \((K_{\delta} \delta_f)_{\text{max}}\) of tool end in Fig.10.

Figure 18 shows change of estimated cutting edge position to rotational angle in up milling. Here, open mark represents the deflection \(K_{\delta} F_y\) of tool end estimated from normal force. Solid mark represents the estimated distance \(D_F\) from cutting edge to ideal machined surface. The rotational angle at the moment when cutting edge is closest to machined surface changes to the negative direction with increase in machining error such as the result of Fig.11.

Figure 19 shows relation between machining error \(e_y\) and rotational angle \(\phi_{\text{min}}\) at minimum value of distance from cutting edge to ideal machined surface. Open mark represents the rotational angle at measured minimum value \((D_F)_{\text{min}}\) of distance from cutting edge to ideal machined surface. Solid mark represents the rotational angle at estimated minimum value \((D_F)_{\text{est}}\) of distance from cutting edge to ideal machined surface. In both results, rotational angle \(\phi_{\text{min}}\) gradually decreases with increase in machining error. The rotational angle at minimum value of distance from cutting edge to ideal machined surface shifts to negative direction because the

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**Figure 14:** Change of normal force with increase in axial depth of cut

**Figure 15:** Situations of cutting

**Figure 16:** Relation between maximum value of normal force and maximum value of deflection of tool end

**Figure 17:** Relation between machining error and estimated deflection of tool end
inclination of increase in deflection of tool end increases with increase in the machining error as shown by open mark in Fig.18.

Figure 20 shows relation between machining error $e_y$ and estimated minimum value $(D_f)_{\text{min}}$ of distance from cutting edge to ideal machined surface. Estimated minimum value $(D_f)_{\text{min}}$ of distance from ideal machined surface is very small such as the result of relation between machining error $e_y$ and estimated minimum value $(D_f)_{\text{min}}$ of distance from cutting edge to ideal machined surface in Fig.12.

Consequently, in this research, the moment when cutting edge is closest to machined surface is not the moment when radial direction of peripheral cutting edge is normal to the feed direction of tool but the moment when cutting edge rotates about 2 to 5 degrees short of the angle when radial direction of peripheral cutting edge is normal to the feed direction of tool.

4. Conclusions

Results obtained by up milling tests were as follows

1) Deflection of tool end and normal force at the moment when radial direction of peripheral cutting edge is normal to the feed direction of tool are not proportional to axial depth of cut but they exponentially increase in axial depth of cut.

2) In this research, the moment when cutting edge is closest to machined surface is not the moment when radial direction of peripheral cutting edge is normal to the feed direction of tool but the moment when cutting edge rotates about 2 to 5 degrees short of the angle when radial direction of peripheral cutting edge is normal to the feed direction of tool.

3) The estimated value of machining errors caused by deflection of tool at cutting point obtained from the deflection of tool near tool holder or normal force was approximately corresponding to the experimental value.

5. References


Figure 18 : Change of estimated cutting edge position to rotational angle

(a) $b=1.0\text{mm}, f=100\text{um/rev}, L=25\text{mm}$

(b) $b=1.0\text{mm}, f=150\text{um/rev}, L=35\text{mm}$

Figure 19 : Relation between machining error and cutting angle at minimum value of distance from cutting edge to ideal machined surface

Figure 20 : Relation between machining error and estimated minimum value of distance from cutting edge to ideal machined surface