The Effects of High Feed Rate of Hardened Steel Milling upon Tool Life
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1. Introduction
Hardened steel used for plastic mold dies or forging dies has started milling in trial, because it has the possibility of cost reduction and shortening delivery time.
It has been reported that the load worked on cutting edges could be reduced in the high cutting speed\(^1\), and especially for milling hardened material. It results in realizing more efficient milling at a higher feed rate and a higher spindle speed using a small ball endmill.\(^2\)\(^3\)\(^4\)

In the meantime, it is known that tool life is drastically reduced by a rotating deviation of cutting edges on usual endmilling. Since the rotating deviation produces the imbalance in cutting force, it seems to result in excessive abrasion on some of cutting edges. However, in case of milling with a small ball endmill, it was reported that there was not any significance in the tool life in 20\(\mu\)m deviation or less\(^5\). Thus, the influence of the rotating deviation of cutting edges on the tool life has been unclear in the high spindle speed milling using a small ball endmill.

In this paper, the tool displacement and cutting force during milling are measured simultaneously for a small ball endmill with 2 cutting edges, and the correlation between abrasion and a rotating deviation of cutting edges is examined. Furthermore, the procedure to reduce the imbalance of tool wear is also proposed.

Table 1: Experimental conditions

<table>
<thead>
<tr>
<th>Specifications of ball endmill</th>
<th>Cutting conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool radius 1mm</td>
<td>Spindle Air bearing</td>
</tr>
<tr>
<td>Shank diameter 4mm</td>
<td>Spindle speed 29000 min(^{-1})</td>
</tr>
<tr>
<td>Number of teeth 2</td>
<td>Feed rate (S_z) 0.1mm/tooth</td>
</tr>
<tr>
<td>Material WC+(Ti,Al)N clad</td>
<td>Coolant Dry</td>
</tr>
<tr>
<td>Axial depth of cut 0.2mm tool life test 0.5mm</td>
<td></td>
</tr>
<tr>
<td>Radial depth of cut 0.2mm tool life test 0.5mm</td>
<td></td>
</tr>
</tbody>
</table>

2. Experimental method and conditions
2.1 Measurement of tool displacement and cutting force
Tool displacement on cutting edges was calculated from the displacement at the tool shank bottom during free run or milling. The rotating deviation on the cutting edges in feed and transverse directions was calculated from the fluctuation of tool displacement and cutting force. The cutting force was measured on a measurement stage on the work table of a machining center (Fig.1). The frequency response of the dynamometer was even up to 10kHz in x and y directions using a capacitance type gap sensor. The signals from the dynamometer and the gap sensor were acquired in PC at the 10kHz sampling rate. Milling conditions are shown in Table 1.

2.2 Evaluation of tool life
Tool life tests were carried out under the milling conditions shown in Table 1. The tool displacement and cutting force were measured in the initial state of a ball endmill. After 120m milling the maximum width of flank wear \(V_{Bmax}\) was measured using SEM, and cutting force was also measured.

Climb milling toward the inside from the outside was applied on the top surface of a workpiece (JIS SKD61, 40HRC), while it is paralleled for each side. Because, the arc of contact with a workpiece is considerably lengthened at the inside corners to bring abnormal abrasion on cutting edges, when it is milled toward the outside from the inside.

In usual tool life tests of the uni-directional milling, it becomes the intermittent milling which produces the steep and cyclic temperature gradient accelerates damage on cutting edges. Therefore, the spiral milling where a chisel on the ball endmill tip is always in contact with the workpiece surface, was applied to the following tool life tests.

3. Experimental results and discussion
3.1 Rotating deviation and tool life
At first, tool life tests were carried out at such high tool stiffness as the extrusion of the tool L is 11mm. Examples of x component \(F_x\) and y component \(F_y\) are shown in Fig.2. The maximum normal component of cutting force \(F_n\) can be estimated from \(F_x\), \(F_y\) and rotating angle \(\theta\) where true depth
of cut reaches maximum. In case of the figure, the ratio of maximum $F_n$ on both cutting edges is given as 1.36, resulting in the true cutting depth of cut ratio 1.36.

A photograph of the worn cutting edges is shown in Fig.3. Each $V_{B_{\text{max}}}$ on both cutting edges is $122\pm2.5\mu m$, $66\pm2.5\mu m$ respectively, and the ratio of them has reached 1.85. On the other hand, though Fig.4 is a photograph of the cutting edges, when both normal components of cutting force were almost equal to each other in the initial cutting state. According to the figure, each $V_{B_{\text{max}}}$ on both cutting edges is $90\pm2.0$ and $96\pm1.4$ respectively, resulting in the ratio between them as 1.07. One of both cutting edges is abraded rapidly by the rotating deviation between them in the former ball endmill (Fig.3) in comparison with the latter(Fig.4).

The relation of the abrasion and the rotating deviation of cutting edges can be also explained according to analyzing a locus of resultant force vector $F_{xy}$ ($F_x$, $F_y$) during 1 revolution, as shown in Fig.5, in the initial state of cutting edges in correspondence to Fig.3. The large continuous line locus and the small dotted line locus in a counter clockwise direction are respectively induced by the revolution of both cutting edges. Two loci are apparently different from each other.

3.2 Reduction of effect of the rotating deviation

As shown in Fig.6, the milling model around a cutting edge at any rotating angle on xy plane is considered. From the equilibrium of the force applied on the cutting edge,

$$d_{t_r} = \frac{k_e}{k_m} d_s, \quad e = \frac{k}{k+m_e} d_s$$

are lead. Where,

- $d_s$ : setting depth of cut
- $k_m$ : relative stiffness between a ball endmill and a workpiece
- $e$ : relative elastic deformation at a cutting edge
- $d_{t_r}$ : true depth of cut
- $k$ : cutting stiffness

$k_e = d_{t_r} k_m$

In case that $d_s = d_s_0 \pm d$

$$d_{t_r} = d_{s_0} + \frac{k_{e_0}}{k_m} d \delta - \frac{1}{k_m} \frac{1}{k_m} d \delta$$

$$e_{+} = \frac{k}{k_m} d_{s_0} + \frac{1}{k_m} d \delta, \quad e_{-} = \frac{k}{k_m} d_{s_0} - \frac{1}{k_m} d \delta$$

where

- $d_{s_0}$ : average setting depth of cut
- $\delta$ : rotating deviation of cutting edges.

True depth of cut and elastic deformation converge in several rotations of a end mill, because of $0 < k/(k+k_m) < 0.3$ in ordinary ball endmilling process. The fluctuation terms in eqs. (2),(3) seem to be a dominant factor in tool abrasion. Setting depth of cut $d_s$ at a rotating angle $\theta$ relative to the tool feed direction is
nearly equal to $S_x \cos \theta$, if $S_y < R$ (R: cutting radius). In the meantime, $\delta$ is constant. Tool stiffness can be representative of the relative tool stiffness $k_m$.

The true depth of cut ratio $d_{tr+}/d_{tr-}$ is written as

$$
\frac{d_{tr+}}{d_{tr-}} = \frac{k_m}{k_m + k} \frac{d_{x0}}{d_{x0} - \frac{k_m}{k} \frac{d_{tr+}}{d_{tr-}}}
$$

from eq. (2). As $k_m/k$ is small, the true depth of cut ratio $d_{tr+}/d_{tr-}$ is close to 1, and the disproportion of the cutting force decreases. The estimated results of $d_{tr+}/d_{tr-}$ relative to stiffness ratio $k_m/k$ are shown in Fig.7 in changing the parameter $\delta/d_{x0}$ in eq.(4). It is clarified that the effect of $\delta$ on the true depth of cut diminishes to reduce the imbalanced abrasion of cutting edges, when the tool stiffness is low in this figure. The above-mentioned discussion is applied to the milling not only with small ball endmills but also with general endmills.

3.3 Effect of tool stiffness on tool life

The effect of the tool stiffness on the tool life is examined by changing extrusion length $L$ as shown in Table 2, for confirming the predicted results. However, in case of tool d, the cutting edge was broken just after touching the endmill on a workpiece. So it was not possible to continue the tool life tests. $V_{B\text{max}}$ was measured after 120m milling. The values except L in Table 2 are calculated in the following.

<table>
<thead>
<tr>
<th>L</th>
<th>mm</th>
<th>11</th>
<th>18</th>
<th>22</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_m/k$</td>
<td>25</td>
<td>6.4</td>
<td>3.8</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Force ratio $F_{n\text{max}}/F_{\text{min}}$</td>
<td>1.37</td>
<td>1.24</td>
<td>1.18</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>$\delta$</td>
<td>$\mu$m</td>
<td>11</td>
<td>9.3</td>
<td>8.2</td>
<td>-</td>
</tr>
</tbody>
</table>

An example of the tool displacement in x direction is shown in Fig.8 using tool b. A continuous line and a dotted line show the displacement during milling $e_x$ and during free-run $e_{x0}$.

In Fig.8, the followings are recognized:
1) The distance between the milling curve and the free-run curve means the elastic deformation on a cutting point in x direction.
2) 2 spikes in one revolution on the milling curve mean the maximum tool displacement induced by milling at the maximum uncut chip area.

3) Cutting edges are always contact with a workpiece, because some elastic deformation always exists through the milling test.

The mean elastic deformation $\bar{e}_{x\text{max}}$ of the cutting edges at the rotating angles $\theta = \theta_0$ and $\theta_0 + \pi$ is obtained 60.3$\mu$m in x direction. In the same way, $\bar{e}_{y\text{max}}$ in y direction at $\theta = \theta_0$ and $\theta_0 + \pi$ is obtained as 39.1$\mu$m. Therefore, the mean normal deformation $\bar{e}_{\text{max}}$ of cutting edges at $\theta = \theta_0$ is calculated as 10.59$\mu$m. $k$ is obtained as 0.13N/µm by substituting $e_{\text{max}} = 10.59\mu$m, $d_{x0} = 66\mu$m and experimented data $k_m = 0.81$N/µm into in eq. (5).

$$
E = \frac{e_+ + e_-}{2}, \quad k = \frac{E}{d_{x0} k_m}
$$

The points a-c in Fig.7 show the milling results using tools a-c as $\delta/d_{x0} \approx 0.15$ at $\theta = \theta_0$.

A photograph of the worn cutting edges using tool c is shown in Fig.9. Each $V_{B\text{max}}$ on 2 cutting edges is almost equal; 74±3.5, 74±3.5$\mu$m respectively, so $V_{B\text{max}}$ ratio $\approx 1.01$. The roughly uneven cutting stripes are observed on each flank of tool c and are smaller in the amplitude than that in the case of tool a in Fig.3. The amplitude on each flank in tool b indicates intermediate value between the other tools.

The relationship between $k_m/k$ and $V_{B\text{max}}$ ratio at $\delta \approx 10$µm is shown in Fig.10. It is verified that $V_{B\text{max}}$ ratio rapidly decreases with the decrease of the tool stiffness. By lowering the tool stiffness, imbalanced abrasion of cutting edges can be suppressed to extend the tool life at the stiffness as low as a break-free ball endmill. In the range of present experiments, it is possible to achieve $V_{B\text{max}}$ ratio <1.06, even if a rotating deviation $\delta$ of 10$\mu$m exists, when stiffness ratio is in
3.8 < k_m/k < 6.4. \( V_{B\text{max}} \) was plotted in Fig.11. The error bar is the 95% confidence limit. A mean value of \( V_{B\text{max}} \) increases with the increase of \( k_m/k \). This is because the uneven undulations on both flanks appear as shown in Fig.3. Especially, it tends to intensify distinctive wear on the boundary.

3.4 Effect of endmill stiffness on true cutting distance

In the reason why \( V_{B\text{max}} \) becomes unbalanced on both cutting edges, the true cutting distance ratio \( l_1/l_2 \) would increase, when the tool stiffness is high. Since both cutting edges are asymmetric, the lower cutting edge is detached from the workpiece in the wider rotating angle. However, the rotating angle during detaching decreases, when the tool stiffness is low, and the true cutting distance approaches to equality on both cutting edges.

Eq. (2) is lead to

\[
\frac{l_1}{l_2} = \frac{\frac{k_m}{k} \left( \frac{\delta}{S_z} \right) - \theta_0}{\cos^{-1} \left( \frac{k_m}{k} \left( \frac{\delta}{S_z} \right) - \theta_0 \right)}, \tag{6}
\]

where \( \theta_0 \) is the rotating angle when a cutting edge comes into contact with a workpiece. The correlation of \( k_m/k \) with \( l_1/l_2 \), estimated with eq. (6) is shown in Fig.12, where \( \delta \) is 8.2-11\( \mu \text{m} \) and \( S_z \) is 0.1 mm. According to the figure, \( l_1/l_2 \) increases with the increase of \( k_m/k \), and \( l_1/l_2 \) has reached 1.28 using tool a. This agrees with the ratio of the true cutting time on both cutting edges being 1.3, as the vector locus was analyzed in Fig.5. The increase of \( l_1/l_2 \) dominated by the tool stiffness seems to be another cause of the increase in \( V_{B\text{max}} \) ratio.

4. Conclusions

In high spindle speed and high feed rate milling of the hardened steel using a carbide ball endmill with 2 cutting edges, the relation between the tool life and the rotating deviation was investigated, and the followings were clarified.

1) The uneven cutting force on both cutting edges is enhanced by the rotating deviation and the tool life remarkably decreases, when the endmill tool stiffness is high.
2) The imbalance of the tool wear on both cutting edges can be suppressed to extend the tool life, when the tool stiffness is lowered as well as a break-free ball endmill.

References