In-Process Monitoring of Machining State in Superfinishing

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Abstract:
In superfinishing, it is difficult to monitor the transitions of machining state during machining process. Therefore, to optimize the machining conditions, it takes a lot of time because many workpieces are machined as a trial. To solve this problem, it is necessary to monitor the transition of the machining state during process. In this study, an advanced in-process monitoring method of machining state in superfinishing is developed. We confirm that the transition of machining state can be monitored by calculating the machining force ratio during machining process experimentally.

Keywords: Superfinishing, Machining force, In-Process monitoring, Machining state, Surface roughness, Machining conditions

1. Introduction
The superfinishing is used widely as the final finish method for sliding surface of many machine elements [1-3]. Figure 1 shows the machining process of the superfinishing. As shown in this figure, the surface of the workpiece is rough before superfinishing. Therefore, the superfinishing stone wears at the initial stage of machining process. This state is called “Cutting state”. As the surface of the workpiece is machined, superfinishing stone is loaded with remove chips from the workpiece. In this state called “Finishing state”, the surface roughness of the workpiece is improved. After the machining process is finished, the finished workpiece is detached to load another one that is not finished and has rough surface. In early state of the machining with the changed workpiece, the loaded surface of the superfinishing stone is removed by the rough surface of the workpiece. Therefore cutting process can be recovered automatically by loading the not finished workpiece.

In superfinishing, the transitions of the machining state from cutting to finishing is necessary to obtain the finished surface of a workpiece. However, it is difficult to monitor the transitions of machining state during machining process. Therefore, to optimize the machining conditions, it takes a lot of time because many workpieces are machined as a trial. To solve this problem, it is important to monitor the transition of the machining state during process. In this study, an advanced in-process monitoring method of machining state in superfinishing is developed.

In this developed method, the tangential machining force and the normal one are measured during process. We focus the change of machining force ratio that is the calculated value of the tangential force divided by the normal force. Machining experiments are carried out to verify the developed method. The superfinishing stone wear and stock removal of the workpiece are also measured to compare the change of the grinding force ratio during machining.

In addition, the machining experiments with rapid retraction of superfinishing stone were carried out to investigate the relationship between the calculated force ratio and the trend of improving surface roughness during machining process.

![Figure 1: Mechanism cycle of superfinishing](image-url)
2. Experimental setup and machining condition

Figure 2 shows the experimental setup developed to this study. The superfineishing stone is mounted on the holder. Stone holder is pushed by compressed air to the radius direction of the workpiece and oscillated to axis direction of the workpiece. The 3-component piezo force censor is installed between an air cylinder and the stone holder for the in-process measurement of machining force applied to 3 directions.

The superfineishing stone wear is measured with laser displacement sensor whose laser is irradiated to the end of piston in the air cylinder. The stock removal is also measured with a sizing gage.

Figure 3 shows the trajectory of an abrasive grain fixed on the superfineishing stone. The maximal inclination angle $\theta$ formed by the velocity of the axial direction $V_s$ and that of circumferential direction $V_w$ is calculated by the following equation [4].

$$\theta = \tan^{-1} \frac{V_s}{V_w} = \tan^{-1} \frac{a}{V_w}$$

(1)

Where $a$ and $f$ are the oscillation amplitude and frequency of the superfineishing stone respectively.

The maximal inclination angle $\theta$ is an important factor that has a lot of influence to the transition of machining state in superfineishing [5]. When the superfineishing is carried out under the machining conditions with large maximal inclination angle $\theta$, the machining state is kept cutting [6]. To transit the machining state from cutting to finishing, the maximal inclination angle $\theta$ must be adjusted narrow range.

Table 1 shows the main machining conditions. Maximal inclination angle is changed by adjusting the oscillation the frequency of the superfineishing stone and the number of rotation of the workpiece.

<table>
<thead>
<tr>
<th>Superfinishing stone</th>
<th>WA1200 20A T5 x W30 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machining time</td>
<td>$T = 20$ s</td>
</tr>
<tr>
<td>Oscillation amplitude</td>
<td>$a = 1.5$ mm</td>
</tr>
<tr>
<td>Oscillation frequency</td>
<td>$f = 28.3, 31.2$ Hz</td>
</tr>
<tr>
<td>Workpiece</td>
<td>SUJ2 (HV770)</td>
</tr>
<tr>
<td>Peripheral speed</td>
<td>$V_w = 1.29, 0.702$ m/s</td>
</tr>
<tr>
<td>Maximal inclination angle</td>
<td>$\theta = 5.9, 11.8$ deg.</td>
</tr>
<tr>
<td>Flow of coolant</td>
<td>$Q = 3.3 \times 10^4$ mm$^3$/s</td>
</tr>
</tbody>
</table>

3. In-process monitoring of machining state

Figure 4 shows the measured surface roughness. In Figure 4 (a), it is confirmed that the surface roughness of the machined workpiece is improved compared with Figure 4 (b). Therefore, the machining state transited to finishing only in machining conditions with the smaller maximal inclination angle.
Figure 5 shows the measured superfinishing stone wear and stock removal of the workpiece. In case of machining with lower maximal inclination angle, the superfinishing stone wear and the stock removal are approached asymptotically to constant value during machining process while these measured results continued to increase in the machining condition with higher inclination angle. These results suggest that the workpiece surface is finished without an increase of stone wear in finishing state.

Figure 6 is the measured machining force during machining process. Machined with a lower maximal inclination angle, the tangential machining force $Q$ decreased as the increment of the stock removal stops while the nominal machining force $P$ does not change. The decrement of the tangential force $Q$ suggests that the machining state changed into finishing state from cutting state. Figure 7 is the calculated machining force ratio $P/Q$. The force ratio is increased same as the decrement of the machining force applied to tangential direction $Q$. By calculating force ratio that is a dimensionless number, it is expected that the transition of the machining state can be monitored even though the superfinishing is performed in other machining conditions.

![Figure 5: Stone wear and stock removal of the workpiece](image)

**Figure 5: Stone wear and stock removal of the workpiece**

![Figure 6: Machining force](image)

**Figure 6: Machining force**

### 4. Investigation of the superfinishing process

To investigate the process of the improvement in surface roughness, rapid retraction of the superfinishing stone during machining are carried out. Table 2 shows the main machining conditions. Machining conditions except machining time are same as the previous conditions with smaller maximal inclination angle. Various machining times are prepared to observe the machining state during machining process. Figure 8 shows the appearance of the workpiece and superfinishing stone after machining. The workpiece shown in Figure 8(a) is machined 2 seconds and another one shown in (b) is finished in 20 seconds. As shown in Figure 8(a), the surface of the superfinishing stone did not darken and the surface of the workpiece was not improved. In this case, the machining state did not transit into finishing state. On the other hand, the surface of superfinishing stone darkened and the smooth surface of the workpiece was obtained in machining with long time. This result suggests that the machining state ends with finishing state due to the loading of the superfinishing stone with removed chips.

<table>
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<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Machining time</th>
<th>$T = 2,4,6,8,10,15,20$ s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillation amplitude</td>
<td>$a = 1.5$ mm</td>
</tr>
<tr>
<td>Oscillation frequency</td>
<td>$f = 28.3$ Hz</td>
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<td>Peripheral speed</td>
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</tr>
<tr>
<td>Maximal inclination angle</td>
<td>$\theta = 5.9$ deg.</td>
</tr>
<tr>
<td>Flow of coolant</td>
<td>$Q = 3.3 \times 10^7$ mm$^3$/s</td>
</tr>
</tbody>
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**Table 2: Main machining conditions in rapid retraction experiments**
Figure 8: The machined workpiece at each time

Figure 9: Variation of machining force ratio and other measured value in a superfinishing process

5. Conclusions

In this study, we develop new monitoring method for in-process monitoring method to judge the transition of machining state in superfinishing. Main conclusions obtained in this study are as follows;

(1) Increment of stone wear and stock removal of workpiece stops after the transition of machining state to finishing from cutting.

(2) The machining state can be monitored with calculating the ratio of the machining force. When the machining state changes into finishing from cutting, the value of force ratio $P/Q$ increased to reach 4.

(3) The surface roughness is improved as the force ratio $P/Q$ increases.

References


